(14) AFWAL-TR-80-3067

LEVEL II

(2)

AD A088629

(6) **FLYING QUALITIES DESIGN CRITERIA**

Proceedings of AFFDL Flying Qualities Symposium Held at Wright-Patterson Air Force Base in October 1979.

CONTROL DYNAMICS BRANCH
FLIGHT CONTROL DIVISION

(10) Robert B. Crombie
David J. Moorhouse

DTIC ELECTE AUG 28 1980 C

(11) MAY 1980

(12) 281

(9) TECHNICAL REPORT AFWAL-TR-80-3067
Interim Report, Mar[redacted]79 - Feb[redacted]80

(16) 2403 (17) 05

Approved for public release; distribution unlimited.

FLIGHT DYNAMICS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

342662

80 8 25 143

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This report has been reviewed by the Office of Public Affairs (ASD/PA), is releasable *to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.*

This technical report has been reviewed and is approved for publication.

Robert B. Crombie

ROBERT B. CROMBIE, 1Lt, USAF, Editor
Control Dynamics Branch
Flight Control Division

David J. Moorhouse

DAVID J. MOORHOUSE, Editor
Control Dynamics Branch
Flight Control Division

Vernon O. Hoehne

VERNON O. HOEHNE, Acting Chief
Control Dynamics Branch
Flight Control Division

FOR THE COMMANDER

M. A. Ostgaard

MORRIS A. OSTGAARD, Acting Chief
Flight Control Division

"If your address has changed, if you wish to be removed from our mailing list, or if the addressee is no longer employed by your organization please notify AFWAL/FIGC *,W-PAFB, OH 45433 to help us maintain a current mailing list".*

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

AIR FORCE/56780/8 August 1980 — 450

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFWAL-TR-80-3067	2. GOVT ACCESSION NO. AD-A088 629	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Flying Qualities Design Criteria - Proceedings of AFFDL Flying Qualities held at WPAFB Oct 79		5. TYPE OF REPORT & PERIOD COVERED Interim Report March 1979 to February 1980
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Compiled by: R. B. Crombie and D. J. Moorhouse		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Flying Qualities Group, Control Dynamics Branch Flight Control Division Flight Dynamics Laboratory		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62201F 24030532
11. CONTROLLING OFFICE NAME AND ADDRESS Flight Dynamics Laboratory (FIGC) Air Force Wright Aeronautical Laboratories Wright-Patterson AFB, Ohio 45433		12. REPORT DATE MAY 1980
		13. NUMBER OF PAGES 294
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Flying Qualities Airplane Design Criteria Military Specification Pilot-Vehicle Analysis		

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Proceedings are reported of a symposium/workshop held at Wright-Patterson AFB during 9-10 October 1979. The symposium was sponsored by the Flight Dynamics Laboratory as part of a continuing effort to revise and upgrade MIL-F-8785B, "Military Specification, Flying Qualities of Piloted Airplanes." Flying Qualities specialists were brought together from both industry and government agencies. Formal and informal presentations, plus workshop discussions, were directed towards discussion of flying qualities design criteria. This report contains a record of the presentations and discussions as submitted by the individual authors.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

FOREWORD

This report contains the proceedings of the FDL-sponsored symposium and workshop held at Wright-Patterson AFB on 9-10 October 1979. The papers contained herein were prepared by various authors. The report editors were Lt Robert B. Crombie and David J. Moorhouse of the Flying Qualities Group. The symposium manager was Lt Crombie.

The work was performed under Program Element 62201F, Project 2403, Task 05, Work Unit 32. This is an interim report for the time period of March 1979 - February 1980.

TABLE OF CONTENTS

SECTION I
OPENING REMARKS

OPENING REMARKS

Dr. Walter R. Beam
Office of the Assistant Secretary
(Research, Development and Logistics)
Department of the Air Force

I was very pleased to be asked to open this conference. This group can take much credit for the progress we've been making in flight control --the F-16, the F-18 and the AMST. I recall that the early state-of-the-art could be characterized by the longitudinal free-stick and fixed-stick stability and that was it. In more recent times you have put the pilot in the loop; he's neither "free" nor "fixed". By understanding him, you have learned finally to cope with pilot-induced oscillations. The early days put emphasis on flying straight and level with modest angle of attack. But now you can handle many with aspects of high-angle-of-attack, and the post-departure regime. In the flying qualities area, obviously, we are moving toward what are now called six-degree-of-freedom systems, in which the conventional control capabilities must be enhanced. We can make the airplane fly more or less straight up, or straight to the side, but we still haven't characterized just how best to command those motions. With the six degrees of freedom you've either got to have six control degrees of freedom, or "fudge it". I've seen several versions of this kind of control, and it's looking better (i.e. more natural to use) every time.

The multi-function control/display seems to be permanently with us; it's the only known way to portray a complex weapon system in shrinking panel-space. The software which controls the mode of weapon system and display has become a critical piece of the weapon system design. The pilot's got to understand very quickly what mode he's in, otherwise he will get in trouble. We are considering modes of operation that are enough different from one state (for example, strafing) to another that one just won't be able to get to some places he'd like to be in an instant. In years past, the only answer was to provide controls for the fingers, elbows, ankles and so on, to move a dozen or more control surfaces. Today, with full-up fly-by-wire, we can preplan any number of automatic control couplings for different mission phases. A thing that is very challenging is the opportunity, presented by programs such as AFTI, to fly the aircraft automatically or semi-automatically to meet a solution in 6-dimensional space such that one can deliver weapons while highly maneuvering. In the past, need for a precision straight-line approach in bombing has made the attacker highly vulnerable to surface weapons. Releasing weapons in such a maneuver has to be done by automatic means. An important question is: how much flying does the pilot do, and how much does the autopilot. It is a challenging one.

Another area that should motivate this group is VTOL and STOL concepts. Pressures still grow toward overcoming the problems of operating on emergency or battle-damaged airfields. If those pressures can result in cost-effective airplanes, we'll probably get some.

The mode-blending business in flight control is something which must be solved in AFTI. This is, when you switch from one mode to another mode, how does the system make the transition, as a function of aircraft state and control positions? That's principally a safety matter.

When one mode and another are very different, and a control actuator has one function in one mode but another function in the other mode, some system guy has to sit down and decide what to do. And there will be a large number of cases to be verified.

We're going to see a lot more exciting action in the digital flight control business. We have really only scratched the surface, though there have been some very key experimental activities in aircraft and space vehicles. The major benefit of digital flight control is that it allows major functional changes to be made in the flight control system through software alone. However, software is a strange mistress; and you had best understand thoroughly what you are doing, else results can be hair-raising. Designing the functional operation, let's say for an automatic-tracking aerial gunnery mode will be much more complex than implementing a 3-axis autopilot of the conventional sort. The problem is not so simple as that of aiming the airplane toward the target. What's the pilot doing? Will he be "out of the loop", possibly suffering from vertigo so that he will not really care? Or, if he's in the loop, how can we make him more effective? How can we take an individual who has been acting as a human loop-closer in a servo system and use him as an adaptive "adjustor" rather than a servo-follower? Rather than putting him in-line, can we give him coarse tracking, or merely supervisory control and still give him the feeling that he's in charge? A very interesting problem.

There is a serious question as to whether, in the future, we should assign the pilot <u>any</u> tracking tasks such as getting the gun or bombsight lined up. General speaking, tracking tasks tend to absorb brain power to a degree which is probably unaffordable in a complex combat environment. If one is in a tracking loop of one (or more) cycles per second time constant, you are full time at that task. The task is even tougher with limited control authority, requiring constant attention to avoid permanent loss of track. How, then, do we move to take the pilot out of the loop, replacing him by a superior sensor, where the pilot flys for strafing, flys a fast-response amplifier, and letting his more facile brain be used for less time-critical but more subtle decisions? Another facet of the overall problem is that of evasive maneuvering. Should autopilots also manage evasive maneuvers? This brings up the very broad question of the pilot-as-passenger.

The tactical Air Force pilot probably would not like to be thought of as a passenger in his own plane; however, in the large transport business, most of the time those $75,000-a-year pilots are passengers. The airplane is pretty much flying itself except in emergencies. With the pilot acting in a supervisory role, he's mostly a back-up to the automatic systems. He must be able to take the controls in an "exceptional event". But how does one know when there is an exceptional event? Blow a horn or a siren? One of the most serious problems with emergency warning systems is keeping the man enough involved, that when the time comes he can take over. The entire issue of warning of exceptional events is a fertile field for better man-machine techniques. Most present systems give threshold-type warnings, and demand immediate action. What we would like is a less crisis-oriented approach, perhaps. Angle-of-attack indicators on modern aircraft can be much more helpful than "stall horns".

I am getting increasingly concerned about the depth of our understanding of the pilot; his work loading is growing rapidly. Thus far, analyses have mostly considered the pilot as a link in a linear servo control system. As such, his frequency-amplitude and -phase characteristics are becoming reasonably well known, though they vary from pilot to pilot. This is useful to understand. At least some of the time, the pilot is tracking something. He's tracking an enemy target, or a precision landing. But we understand very little about the pilot as a sensor. Work with visually equipped flight sensors only has increased our curiosity about how the pilot uses visual and motion cues. The pilot, after several thousand hours of flying, gets very good at it. He ignores motion cues during instrument flight because the motion cues are untrustworthy. (In order to understand the motion cues you must perform an integration; the brain is not a good integrator.) Visual cues are best, but motion cues give indication of acceleration while visual cues "read out" only position and relative velocity. Chances are that the advanced 6-degree-of-freedom aircraft will demand additional cueing indications; perhaps our work with simulators will provide the clues to better cues!

The pilot's perception of aircraft handling or aircraft flying qualities is very important. We design a good airplane, one that has no bad characteristics, and pilots don't like it. Except for unresponsiveness or instabilities, however, it's hard for most pilots to pinpoint the subtle problems. Some flight simulators, for example, have had unpleasant handling, which only detailed examination of the design could resolve. An everyday example of operator perception of performance is found in automobiles. An automobile which has a weak throttle-spring will seem to give responsive performance. One with a strong throttle spring feels sluggish. This you have on airplanes too. If the controls are stiff or must move far, it's unresponsive; if control gain is large and restoring force small, it may be termed "too sensitive". Most of the data on this topic is totally subjective. We really don't know much about the effect of control motions--including reaching for switches and knobs--on the difficulty of the overall piloting job.

An interesting problem that's coming up (I'm sure you've been aware of the A-10 two-seat version) is flying an airplane through a "scope" image of the outside world. Intuition says that too small a screen will greatly complicate the problem; it also suggests that a screen with the same visual coverage one would get in clear weather. Intuition also suggests that a 30-per-second frame-rate is better than a typical radar scan rate. In all cases, intuition needs to be bolstered by testing and analysis. Such a display lacks stereoscopic effects, but how important is stereo vision when objects are hundreds of feet away? At those ranges, we probably depend on the change of perspective as we move closer to an object. If we understood better the use of visual information in terrain following/avoidance, it would no doubt help us do a better job in other visually-controlled tasks.

Low-speed handling will probably be receiving more and more attention. The special control problems of either propulsive lift or vectored thrust (or anything close to the ground) are most important. Also, the devices that we put on the aircraft to slow us down or to give extra lift change the handling characteristics significantly. Relatively little work has been done on handling characteristics at low speeds, and in ground effect. A good multimode flight control will need to address specifically the takeoff and landing. The delicate issue of flying qualities at moments when a part of the weight of the airplane is on the landing gear is often put aside because the transition takes only a few seconds. However, there are probably more accidents in those few seconds, per unit flying time, than in any other phase. There are many other factors for which fly-by-wire can compensate: External stores--we have to put things on the outside of many airplanes; we have widely varying fuel loads. An interesting question is whether we should have systems that can adaptively adjust ones that are preprogrammed and coupled to stores and fuel management systems. We will need to couple flutter control and flight control "loops", and eventually (as in Apollo) will need to address schemes which will compensate for unplanned events such as battle damage.

I believe that we are in one of the most challenging areas of aeronautical development, one in which analytical techniques can be nicely combined with experimental techniques, and one in which many disciplines must work together. One must understand aerodynamics in order to understand the control problems; he must understand control system techniques to understand what and how much control surface is needed. He must also understand the "people problems", the subjective responses of an individual flying an airplane. With a close interplay of all three elements, the new technology promises major improvements of the usefulness of our military aircraft.

SECTION II

FORMAL PAPERS

Paper No. 251

HIGH AOA LATERAL-DIRECTIONAL DESIGN GUIDES AND CRITERIA - A PILOTED SIMULATION ASSESSMENT

Donald E. Johnston

Presented at the

Flying Qualities Workshop
Wright-Patterson AFB, Ohio
October 1979

HIGH AOA LATERAL-DIRECTIONAL DESIGN GUIDES AND CRITERIA — A PILOTED SIMULATION ASSESSMENT

INTRODUCTION

For a number of years, a principal concern of the fighter aircraft industry has been design for high AOA departure resistance. Departure is defined (Ref. 1) as:

> "...the event in the post-stall flight regime which precipitates entry into a post-stall gyration, spin, or deep-stall condition. The departure may be characterized by divergent, large-amplitude, uncommanded aircraft motions, such as nose-slice or pitch-up. Departure is synonymous with complete loss of control."

However, pilots generally place a rate threshold on the uncommanded motion. Rates below the threshold are interpreted as natural warning that a limit is being (has been) reached and to back off to regain positive control. If the aircraft returns to controlled flight the aircraft is considered departure resistant. Rates above the threshold raise the distinct problem of the pilot not being able to prevent the uncommanded motion from continuing. If this is the case (e.g., after a slight delay in neutralizing controls), the aircraft is considered departure susceptible. The aircraft is considered extremely susceptible to departure if departure generally occurs with the normal application of pitch control alone or with small roll and yaw control inputs (Ref. 1).

Thus, departure susceptibility involves two aspects: open-loop static and dynamic stability, and pilot/vehicle closed-loop stability. The first is relatively straightforward to predict or demonstrate, including the influences of steady aggravated control inputs. The second is not since it may be dependent upon pilot technique and/or skill.

The assessment of high AOA flying characteristics reported in this paper has resulted from interaction between two research programs* sponsored by

*Contract F33615-76-C-3072, Identification of Key Maneuver-Limiting Factors; Contract F33615-78-C-3604, High AOA Design Guides and Flying Qualities Criteria.

the FDL/FGC. One is concerned with identifying causal factors relating to high AOA departure susceptibility, warning, and severity. The other is addressed to a survey of high AOA design guides and criteria used in early or configuration preliminary design stages and an assessment of the effectiveness of the guides and criteria.

The following presents an overview of the aerodynamic parameters analytically found to dominate high AOA dynamic characteristics; a brief description of the piloted simulation employed to validate the cause/effect predictions; some results of the simulation and comparison with currently popular high AOA design guides; and, finally, an alternative design guide having broader applicability than those currently available.

KEY HIGH AOA PARAMETERS

The key aerodynamic derivatives which were shown in the Ref. 2 analysis to dominate aircraft open-loop departure warning, susceptibility, and severity are summarized in Table 1. On the left are the key open-loop parameters; on the right are the maneuver limiting dynamic characteristics associated with the open-loop parameter. Negative N_{δ_a} or $N_{\delta_{DH}}$ (differential horizontal) is a causal factor of roll reversal. This is nothing new and

TABLE 1

KEY OPEN-LOOP DEPARTURE PARAMETERS

Negative N_{δ_a} or $N_{\delta_{DH}}$	Roll Reversal
Positive M_β	Pitch Up
$\mathcal{L}_\beta, \mathcal{L}_\alpha, \mathcal{L}_p$ N_β, N_α M_β	Wing Rock Nose Slice Roll Divergence

has been observed on a number of aircraft. It is a key parameter in that it signifies the onset of large sideslip excursions in maneuvering flight. The second open-loop parameter identified is M_β, pitching moment due to sideslip. Postive M_β results in pitch-up with sideslip; negative results in pitch-down. The remaining static coupling and cross-coupling derivatives (and the one damping derivative) all contribute to wing rock, nose slice, and roll divergence characteristics. A given aircraft response depends upon the relative values of these six coefficients and one can get any or all of these motions depending upon the coefficient values and ratios. The importance of L_β, N_β, and L_p is widely recognized. In the vicinity of stall, aerodynamic moments generally become highly non-linear functions of both α and β and the cross-coupling derivatives L_α, N_α, and M_β can become quite large at $\beta \neq 0$.

The Ref. 2 analysis also identified key closed-loop departure parameters (Table 2). These are associated with the numerator factors (or roots) for the vehicle motion over which active piloted control is being exerted.

For aileron-only maneuvering control a key parameter is the ratio of ω_ϕ^2 to ω_d^2. The ratio is proportional to LCDP/$Cn_{\beta_{dyn}}$ (e.g., from Refs. 3 and 4), which at zero sideslip derives from the aerodynamic coefficients of Fig. 1, e.g.,

TABLE 2

KEY CLOSED-LOOP DEPARTURE PARAMETERS

AILERON MANEUVERING CONTROL	$\frac{\omega_\phi^2}{\omega_d^2} \sim \frac{\text{LCDP}}{Cn_{\beta_{dyn}}}$	Roll Reversal Wing Rock Roll Departure
RUDDER OR AILERON MANEUVERING CONTROL	$\frac{1}{T_{\theta_3}}$	Nose Slice

$$\frac{LCDP}{Cn_{\beta_{dyn}}} = \frac{Cn_{\beta}\left[1 - \frac{Cn_{\delta_a} C\ell_{\beta}}{C\ell_{\delta_a} Cn_{\beta}}\right]}{Cn_{\beta} \cos\alpha - \frac{I_z}{I_x} C\ell_{\beta} \sin\alpha}$$

Undesirable ratios lead to roll reversal, pilot-aggravated wing rock (PIO), and roll departure. In the presence of sideslip, the expressions become complicated by additional terms involving $C\ell_{\alpha}$, Cn_{α}, Cm_{β}, and trig functions of β.

Another key closed-loop departure parameter for either rudder or aileron maneuvering control (in that either of these tends to produce β at high α) is the previously (Ref. 5) reported zero of the θ numerator which can lie in the right-half-plane. This root results from lateral/longitudinal coupling due to sideslip, is dominated by L_{α} and N_{α}, and leads to an unstable lateral-directional mode (nose slice) due to the pilot controlling pitch attitude with elevator.

The open-loop and closed-loop departure parameters identified in Tables 1 and 2 were selected to be the key variables in the piloted simulation.

SIMULATION

The simulation was performed at the McDonnell Aircraft Company in the 20 ft hemispherical fixed-base dome identified as MACS-1. Physical aspects of the simulation are summarized in Fig. 1 and Table 3. The horizon and target are projected on the inside of the hemisphere. The cockpit is located at the center of the dome. The out-the-window, head-up, and head-down displays and cockpit layout are as indicated in Table 3. Seat cues consisted of normal acceleration and buffet motion provided through an inflatable seat bladder. A TV projection of a gimballed model provided a realistic maneuvering tracking task. Two Air Force flight test pilots experienced in high-angle-of-attack departure and spin testing served as the subject pilots.

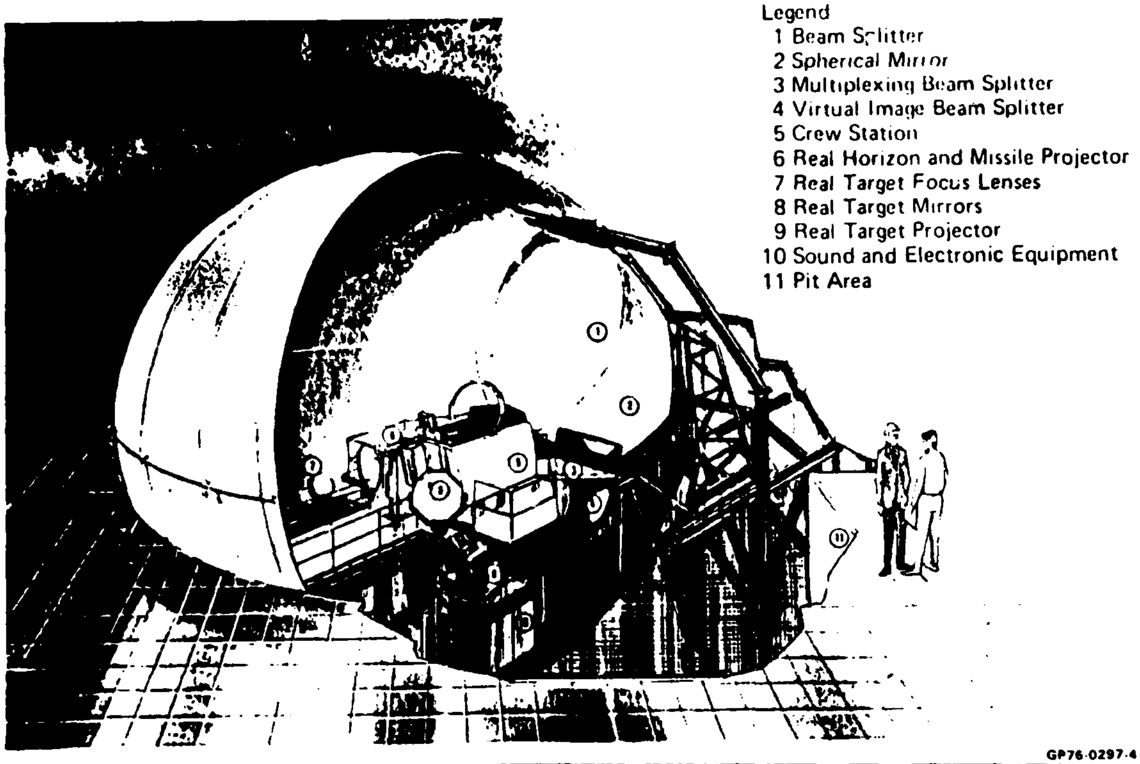


Figure 1. Manned Air Combat Simulator I

TABLE 3. SIMULATION

FIXED BASE:	McDonnell MACS-1 20 ft Dome
DISPLAYS:	HORIZON – 360 deg ϕ, θ, ψ
	HUD – CAS, h, ψ, v.v.
	HDD – $\phi, \theta, \psi, \alpha$, M, etc.
	SIGHT – Fixed Reticle
COCKPIT:	Basic F-4
SEAT CUES:	N_z, Buffet
TARGET:	Gimballed Model TV Projection
PILOTS:	2 – USAF FTC

Table 4 indicates the aerodynamic models and flight control configurations employed in the simulation. The six DOF aerodynamic model consisted of nonlinear coefficients as a function of α and β which were stored in the digital computer as look-up tables. To prevent any discontinuities in aero data for the extreme maneuvers expected in departure and spin, the data were modeled over the α range from −180 to +180 deg and β was modeled over the range of ±90 deg. The aerodynamic modeling was precise for α between 0 and +45 deg and β up to ±30 deg. Beyond these limits the data were extrapolated and faired to prevent discontinuities under all-attitude maneuvering. One basic set of aerodynamic coefficients was employed. Individual roll, yaw, and pitch moment coefficients were then systematically altered to produce characteristics approximating those of the F-4J, the F-14A, and two hypothetical dynamic configurations.

TABLE 4. AERODYNAMICS MODELS AND
FLIGHT CONTROL CONFIGURATIONS

AERODYNAMIC MODELS

- Nonlinear $f(\alpha,\beta)$
- $-180 \text{ deg} < \alpha < +180 \text{ deg}$
- $-90 \text{ deg} < \beta < +90 \text{ deg}$

FLIGHT CONTROL CONFIGURATIONS

- Unaugmented Manual FCS
- Augmented

$$r,\ a_y' \rightarrow \delta_R \quad \text{SAS}$$

$$p_e \rightarrow \delta_a \quad \text{CAS}$$

$$\frac{\delta_{LS}}{(\tau s+1)}\ \alpha \rightarrow \delta_R \quad \text{SRI}$$

Two flight control configurations were employed: an unaugmented manual flight control system typical of the basic F-4J aircraft, and an added augmentation similar to the newer generation of fighter aircraft. In all cases, gains and equalizations were adjusted to be compatible with our airframe characteristics. In the yaw axis, yaw rate and lateral acceleration feedback to the rudder was employed. In the roll axis a command augmentation system was employed in which stick displacement commands roll rate and the roll rate error is used to deflect the roll control surfaces. This portion of the augmentation system is the principal contributor to increased dutch roll damping or stabilization of a mildly unstable dutch roll root. A third aspect of our augmentation system is a lateral stick-to-rudder interconnect which favorably alters the location of the roll numerator zeros, ω_{ϕ}. The lateral stick displacement signal is fed through a first-order lag and a gain which varies with α. The gain is zero for $\alpha < 10$ deg and ramps up to a maximum at $\alpha \geq 20$ deg.

CONFIGURATIONS AND PREDICTED HIGH AOA CHARACTERISTICS

Table 5 summarizes the six configuration matrix employed. The configurations are identified on the left; in the center is the aerodynamic term varied, and on the right are anticipated high AOA characteristics based upon analysis and open-loop time responses. Configuration A has the aerodynamics of the basic F-4J aircraft. Both flight control configurations were employed with this aerodynamic model; A_1 is unaugmented and A_2 is augmented. For A_1 a sequence of roll reversal, wing rock, nose slice, and finally rolling departures is predicted with increasing AOA. For A_2 the augmentation system and crossfeed are expected to minimize or eliminate the roll reversal and wing rock predeparture warnings. Thus, the predicted characteristics are nose slice followed by rolling departure. For B the aerodynamic roll damping parameter, C_{ℓ_p}, was increased. This aero configuration was used only with the basic manual flight control system in order to compare the high AOA stall/departure characteristics of an aircraft with naturally high roll damping (Configuration B) with that obtained with artificially augmented roll damping (Configuration A_2). For B predicted departure characteristics are roll reversal, nose slice, and rolling departure.

TABLE 5. CONFIGURATION MATRIX

CONFIGURA-TION	FCS	AERO VARIANT	PREDICTED CHARACTERISTIC
A_1	BASIC	BASIC F-4J	ROLL REVERSAL (RR) WING ROCK (WR) NOSE SLICE (NS) ROLL DEPART (RD)
A_2	AUG		NS RD
B	BASIC	INCREASED C_{ℓ_p}	RR NS RD
C_1	BASIC	$\left.\begin{array}{l}\text{INCREASED } C_{\ell_\beta}\\ \text{DECREASED } C_{\ell_\alpha}\end{array}\right\\} 15 < \alpha < 45$	RR WR RD
C_2	AUG		NONE $\left\\{\begin{array}{l}C_{n_{\beta_{dyn}}} > 0\\ \text{LCDP} > 0\end{array}\right.$
D	BASIC	$\left.\begin{array}{l}\text{INCREASED } C_{n_\beta}\\ \text{DECREASED } C_{n_\alpha}\end{array}\right\\} \alpha > 15$ POSITIVE C_{m_β}	RR WR PITCH UP

Warning in the form of wing rock should not be present due to the large roll damping of this configuration. For C the rolling moment coefficient as a function of α and β was modified in the α range between 15 and 45 deg to approximate that of the F-14A aircraft. The unaugmented Configuration C_1 is predicted to exhibit roll reversal, wing rock, and rolling divergence with increasing AOA but no nose slice. The augmented flight control system was also employed with C to determine if it would improve or degrade the departure characteristics of this configuration. The airframe and flight control characteristics were selected so that $C_{n_{\beta_{dyn}}}$ and LCDP are both greater than zero throughout the usable AOA range for the configuration. On the basis of these parameters, no departure tendency is anticipated for this configuration. Finally, D employed altered static yawing moment characteristics for AOA greater than 15 deg to increase C_{n_β} and decrease C_{n_α}. The end result is an airframe mildly directionally unstable at AOA greater than 25 deg which should exhibit roll reversal and wing rock warnings. A second modification incorporated in D was a change in sign of C_{m_β} to provide positive pitching moment with sideslip. This should result in pitch-up and would be expected to aggravate any high AOA departure characteristics. All other configurations had negative C_{m_β}.

The susceptibility to, and severity of, departure may be predicted for four of the configurations via the Weissman departure/spin criteria (Ref. 4) and the more recent Bihrle criteria (Ref. 6). Both of these are basic airframe (i.e., unaugmented) predictors in that they are based upon static aerodynamic coefficients. The augmentation system employed alters the effective static as well as dynamic characteristics but, unfortunately, augmentation and SRI influence is frequency dependent and therefore cannot be readily shown via either criterion.

The Weissman criterion (Ref. 4) is a plot of $C_{n_{\beta_{dyn}}}$ vs. LCDP divided into four regions of increasing departure and spin susceptibility and severity (Fig. 2). The loci of our unaugmented airframe parameter values over the AOA range of 16-35 deg are shown by the various symbols: circles represent Configurations A_1 and B (since C_{ℓ_p} has no influence on either parameter), squares represent Configuration C_1, and triangles Configuration D. The criteria predict high departure/spin susceptibility with strong rolling departures for Configurations A_1 and B; moderate susceptibility and rolling departures for Configuration C_1; and no departures for Configuration D. Thus, all regions of departure susceptibility and severity are exercised with the aerodynamics selected. (Based on steady-state gains, the augmentation system would shift Configurations A and C off-scale at the top of Fig. 2, a region predicting no departure tendency. But, again, the loci are frequency-dependent and cannot be readily demonstrated by this criterion.)

The Bihrle criterion (Ref. 6) relates roll reversal and departure susceptibility to the raw static aerodynamic coefficients $C_{n_{\delta_a}}$, C_{n_β}, and

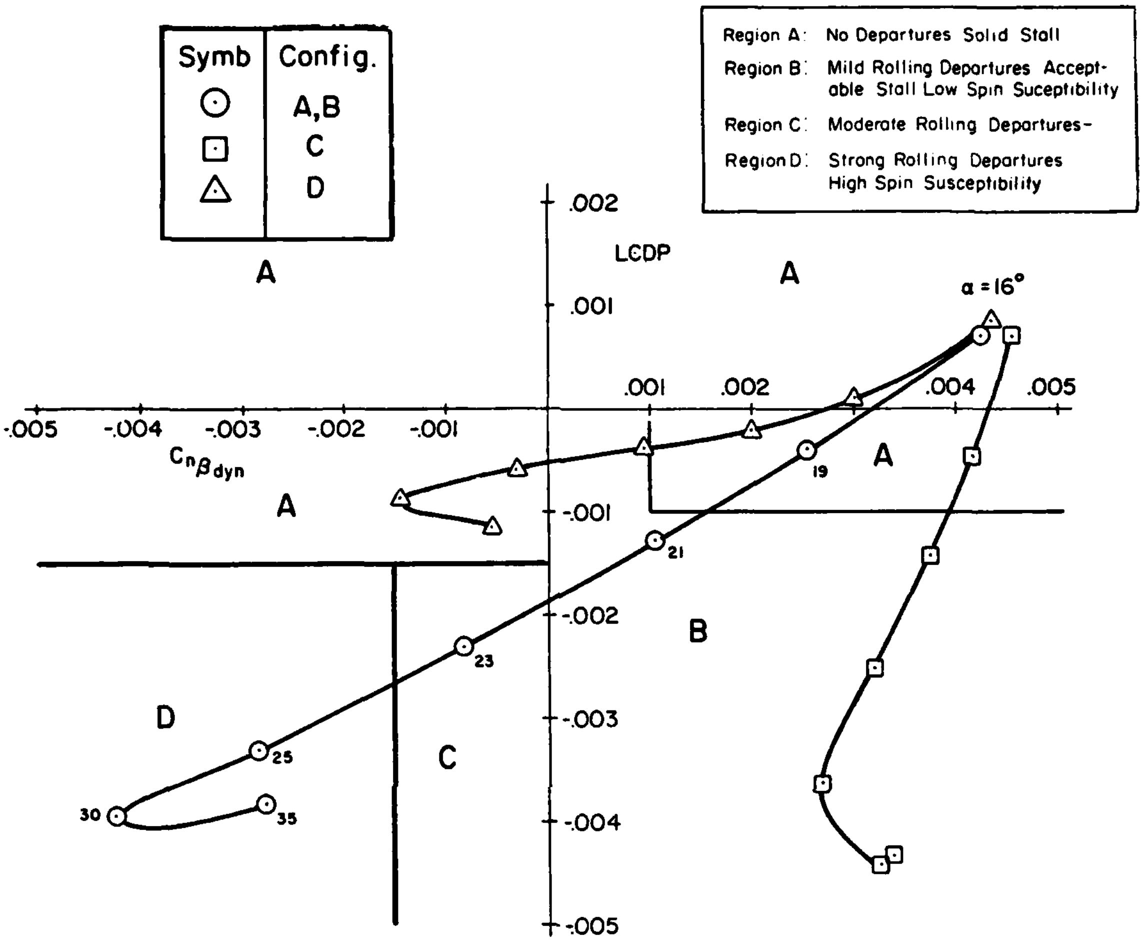


Figure 2. Weissman Criteria Predictions

C_{ℓ_β}. Figure 3 presents the boundaries for an aircraft exhibiting adverse Cn_{δ_a}. Two boundaries are included. The upper, dashed boundary is the roll reversal criterion. Above the dashed line no roll reversal is predicted; below the dashed line the aircraft should exhibit roll reversal. The lower solid boundary is the departure criterion. Again, above the boundary there is no departure; below the boundary the criterion predicts a departure. The circles identify Configurations A and B over an AOA range from 10 deg to 40 deg, the squares identify Configuration C for the same AOA range, and the triangles identify Configuration D.

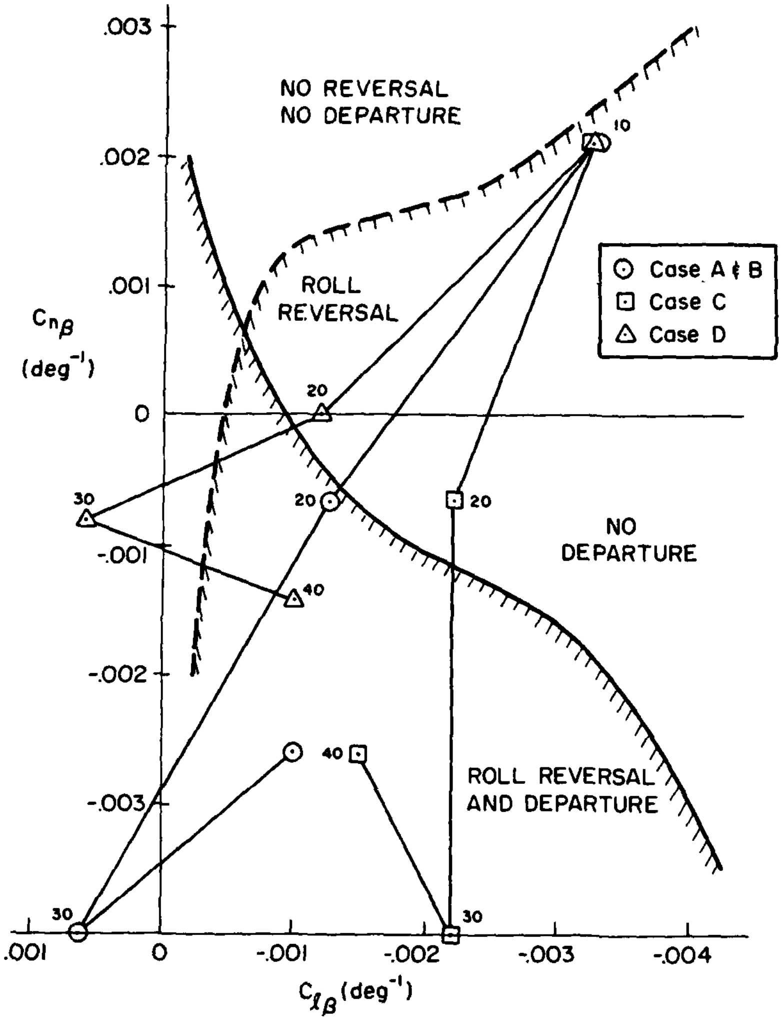


Figure 3. Bihrle Criterion (Adverse Cn_{δ_a})

The interpretation is that the Bihrle criterion predicts, for the Aircraft Cases A and B: roll reversal above about 12 deg AOA. At approximately 20 deg AOA the region is entered in which departure might be expected. Out to 30 deg AOA, C_{ℓ_β} is small while C_{n_β} is large, negative, and one would expect a strong directional divergence or nose slice characteristic. At yet higher angles of attack, C_{ℓ_β} increases negatively while C_{n_β} decreases and one might expect more of a rolling divergence characteristic.

Configuration C, on the other hand, stays relatively close to the departure criterion boundary and is well to the right of the roll reversal boundary. Therefore, the criterion predicts this configuration to exhibit significant adverse yaw, roll due to sideslip, and, above 20 deg AOA, rolling departures.

Configuration D stays much closer to either of the two criterion boundaries. It therefore lies in a gray area because slight shifts in either of the criterion boundaries could change predictions regarding both roll reversal and departure tendencies. The interpretation is that Configuration D should have mild, if any, roll reversal characteristic and mild, if any, rolling departure characteristic.

There is considerable similarity between the AOA loci plots of Figs. 2 and 3. This is because LCDP $\doteq Cn_{\beta}$ when $C\ell_{\beta}$ and $Cn_{\delta a}$ are small and $Cn_{\beta dyn} \sim C\ell_{\beta}$ when $Cn_{\beta} << C\ell_{\beta}$. Thus, one should expect the two criteria to be substantially in agreement in the region of interest, i.e., where static and/or dynamic stability is critically low. The Bihrle criterion, however, is somewhat the less sophisticated of the two and therefore may be easier to apply in the midst of wind tunnel testing.

In summary, the six vehicle configurations selected are predicted to exhibit a broad spectrum of high AOA departure warning, susceptibility, and severity characteristics for assessment by the pilots.

RESULTS

The high AOA characteristics actually observed by the two pilots differed widely, as did their assessments of departure susceptibility and severity. For example, Table 6 presents departure susceptibility ratings given by each using the definitions of resistant (R), susceptible (S), and extremely susceptible (ES) from Ref. 1. The ratings were given for bank-to-bank and wind-up turn tracking task maneuvers similar to those recently developed for flight test evaluation of flying qualities (Refs. 7 and 8).

The first impression is to throw everything away and start over. However, both pilots were highly experienced and, recognizing the potential

TABLE 6

COMPARISON OF PREDICTED AND ACTUAL
DEPARTURE SUSCEPTIBILITY RATINGS

DEPARTURE SUSCEPTIBILITY			
CONFIG.	PRED.	P-I	P-II
A_1	ES	R	$\boxed{\text{ES}}$
B	ES	S	$\boxed{\text{ES}}$
C_1	S	$\boxed{\text{S}}$	$\boxed{\text{S-ES}}$
D	R	$\boxed{\text{R}}$	$\boxed{\text{R}}$
A_2	NA	R	ES
C_2	NA	R	S

impact of the study, highly motivated. Therefore, an in-depth analysis of recorded pilot commentary and motion strip charts was performed and supported by additional closed-loop analysis. From these it was deduced that the two pilots were using widely differing tracking and control techniques.

Pilot P-I was cautious and sensitive to onset of instability. He observed all of the departure onset warnings available and adjusted his gains to follow the decreasing roll control stability boundary until he considered path control was no longer possible. Then he would initiate recovery controls (stick forward, aileron and rudder neutral) and observe the resulting aircraft response.

Pilot P-II was much more aggressive in acquiring and tracking the target aircraft. He would set his gains for stable tracking at low AOA and then not change them as he rapidly pulled his aircraft into the higher AOA region. Thus he would suddenly cross the stability boundary and depart. This pilot observed no warnings whatsoever due to the rapid transition through the warning region and penetration of instability regions. As a result, he almost always entered post-stall gyrations of varying severity and was rating spin rather than departure susceptibility and severity.

A comparison between departure/spin susceptibility predicted by the Weissman criteria and the ratings provided by the two pilots is also shown in Table 6. Ratings substantially in agreement with prediction are shown in boxes. Obviously the aggressive pilot observed the worst possible characteristics of each unaugmented configuration as predicted by the criteria. The less aggressive pilot experienced something quite different. As noted previously, the criterion does not lend itself to prediction of the frequency dependent augmented airframe characteristics, but these configurations were expected to be less susceptible to departure. This influence was observed only by the less aggressive pilot.

One important difference between prediction and simulation was the nature of departure. Figure 2 indicates predominantly rolling departure with no indication of yaw departure. Our Configurations A, B, and D exhibited initial yaw excursions sometimes followed by roll. Configuration C exhibited three different departure modes which were dependent upon control application at onset of departure. However, a rolling type motion did predominate.

Thus, the Weissman criterion left something to be desired in predicting both the susceptibility to and nature of departure observed by the pilot. The negative LCDP of Fig. 2 indicates that the roll control numerator for lateral stick input has one negative root — or one first-order zero in the right-half-plane (RHP) of a root locus. Figure 4 shows a representative set of pole and zero locations at a frozen flight condition in which LCDP or ω_φ^2 is negative. The roll numerator has two first-order zeros, $1/T_{\varphi_1}$ and $1/T_{\varphi_2}$. When the pilot attempts to control roll, one pole (in this instance the spiral, $1/T_s$) is immediately driven toward the RHP zero and a first-order divergence results. The dutch roll mode is also driven unstable in this example; however, the pilot can adopt lead to stave off this instability, whereas nothing short of opening the loop can prevent the first-order divergence. The more negative LCDP becomes, the further $1/T_{\varphi_1}$ is located in the RHP and the faster the divergence rate potential due to the loop closure. It is further shown in Ref. 2 that

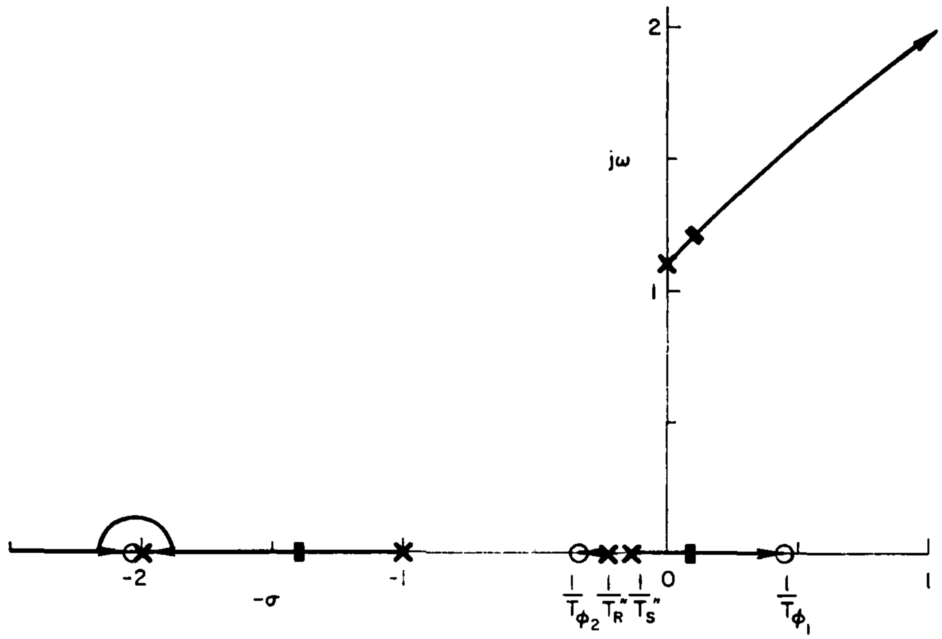


Figure 4. $\phi \rightarrow \delta_a$ Closure with Yaw SAS On

sideslip causes the two first-order zeros to coalesce into a RHP complex pair with negative damping (or real part) identified as $\zeta_\phi\omega_\phi$. Thus, $\zeta_\phi\omega_\phi$ is strongly influenced by the cross-coupling aero coefficients C_{ℓ_α}, C_{n_α}, and C_{m_β}.

The previously noted analysis to identify causal factors behind the widely differing pilot ratings for departure/spin susceptibility produced a strong relationship between pilot ratings for both pilots and penetration of the roll numerator root into the RHP. Figure 5 shows the value of the real part of the numerator root at the instant the pilot decided he had, or was about to, depart and initiated recovery. These values are plotted against this AOA at which recovery was started. (Note this is not the usual jω axis.) The points represent all six vehicle configurations as evaluated by both pilots.

The division between departure resistant (R) and susceptible (S) ratings is seen to lie at roughly −0.5 rad/sec. This corresponds to a time to double amplitude of approximately 1.4 sec. Zeros which lie to the left of this line apparently limit the first-order divergence to a

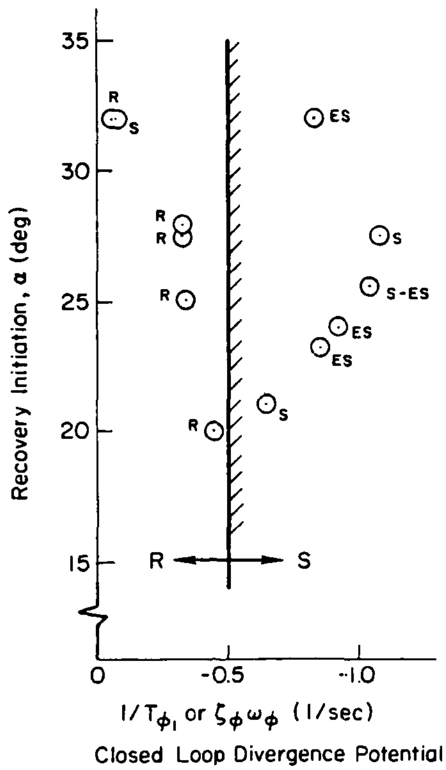


Figure 5. Lateral Closed-Loop Divergence Potential

rate slow enough for pilots to respond and recover. Zeros to the right of the line apparently allow divergence rates so fast that they cannot prevent departure. It is interesting that when initially questioned regarding their personal definition of departure, both pilots indicated a threshold on rate of motion; however, they were vague as to the value (e.g., "maybe 20 or 30 deg/sec, I don't know"). One data point in Fig. 5 violates the boundary. This is the augmented Configuration C_2. In this case the SRI eliminated adverse yaw and thus made the vehicle more departure resistant (as viewed by our cautious pilot). However, it could be departed and then the augmentation produced pro-spin control. The aggressive pilot rated spin susceptibility and apparently rated this configuration accordingly.

The implication is that if the combined aerodynamics and flight control system design is such that $1/T_{\varphi_1}$ never exceeds -0.5 throughout the achievable α range then the airplane will be departure resistant. It should be noted that this places no restriction on open-loop stability. For example, $C_{n_{\beta_{dyn}}}$ can be negative and, in fact, is negative for Configuration D (see Fig. 2) which is rated departure resistant (see Table 6) by both pilots.

Since ω_φ^2 is the dimensional form of LCDP and, in general, $|1/T_{\varphi_1}|^2 \doteq |\omega_\varphi^2|$, then one can relate the above $1/T_{\varphi_1}$ boundary to an equivalent LCDP. For the flight conditions, inertias, etc., employed in this simulation,

$$1/T_{\varphi_1} = -0.5 \doteq \text{LCDP} = -0.001$$

This coincides with Weissman's boundary between Regions A and B for positive $C_{n_{\beta_{dyn}}}$, see Fig. 6; however, it is a little more conservative at negative $C_{n_{\beta_{dyn}}}$. Thus, the results of our simulation are compatible with and support Weissman's empirically derived LCDP boundary. The key difference in the criteria is that $1/T_{\varphi_1}$ is not restricted to airframe lateral-directional static coefficients but can be applied throughout the aircraft development

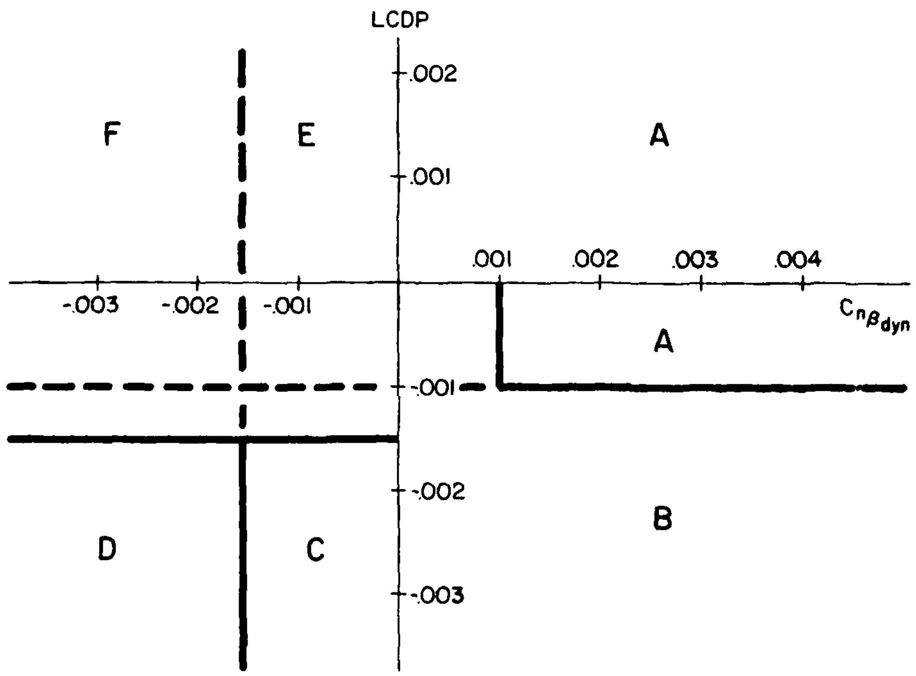


Figure 6. Possible Modifications to Weissman Criteria

cycle, i.e., for the completely coupled 6 DOF airframe plus a full complement of augmentation, stick-to-rudder crossfeed, etc.

In addition, results of our simulation tend to indicate another boundary might be appropriate in the upper left quadrant of Fig. 6 to create two additional regions, E and F. Region E would be classed as mild directional divergence and spin tendency. Region F might be classed as strong directional divergence and spin tendency. Note from Fig. 2 that our aircraft Configuration D, which had mild directional departure characteristics but little or no spin tendency would extend into criteria Region E.

SUMMARY

Analysis and piloted simulation have shown that:

- The high AOA maneuver limiting and departure characteristics of fighter-type aircraft are significantly altered by changing the lateral-directional static aerodynamic coupling and cross-coupling derivatives, L_β, L_α, N_β, N_α, and M_β.

- Departure warning was also influenced by the roll damping derivative, L_p, and the augmentation system. The effectiveness of warnings is highly pilot dependent and cannot be relied upon to guide the pilot into avoiding departure.

- The pilot's perception of departure susceptibility was found to be correlated with movement of one root of the roll numerator for lateral stick control into the RHP of the root locus, i.e., a non-minimum phase zero. If the aircraft high AOA configuration produced a zero, $1/T_{\varphi_1}$, more negative than −0.5 and the pilots could fly the aircraft to such AOAs, it was rated departure susceptible. If this boundary was not or could not be exceeded the aircraft was considered departure resistant. This rating is independent of the sign or magnitude of the dynamic stability parameter $Cn_{\beta_{dyn}}$.

- A value of $1/T_{\varphi_1} = -0.5$ corresponds to an effective LCDP of −0.001 and thus is consistent with and supports the empirically derived LCDP departure boundary developed by Weissman. However, results of the simulation were not in agreement with the types of departure predicted by Weissman in that negative $Cn_{\beta_{dyn}}$ regions produced yaw or nose slice type departures.

It is suggested that as the aircraft design/development cycle progresses past the static wind tunnel phase the Weissman criterion for departure/spin susceptibility be replaced by a negative $1/T_{\varphi_1}$ limit.

REFERENCES

1. "Military Specification of Stall/Post Stall/Spin Flight Test Demonstration Requirements for Airplanes," MIL-S-83691A, Apr. 1972.

2. Johnston, D. E., and D. G. Mitchell, Identification of High AOA Maneuver-Limiting Factors, Systems Technology, Inc., TR-1081-1, forthcoming AFFDL-TR.

3. Moul, M. T., and S. W. Paulson, Dynamic Lateral Behavior of High Performance Aircraft, NACA RM No. L58E16, Aug. 1958.

4. Weissman, R., "Status of Design Criteria for Predicting Departure Characteristics and Spin Susceptibility," J. Aircraft, Vol. 12, No. 12, Dec. 1975.

5. Johnston, D. E., I. L. Ashkenas, and J. R. Hogge, Investigation of Flying Qualities of Military Aircraft at High Angles of Attack. Vol. I: Technical Results, AFFDL-TR-74-61, June 1974.

6. Bihrle, W., Jr., and B. Barnhart, Design Charts and Boundaries for Identifying Departure Resistant Fighter Configurations, NADC-76154-30, July 1978.

7. Sisk, T. R., A Preliminary Assessment of the Transonic Maneuvering Characteristics of Two Advanced Technology Fighter Aircraft, NASA TM X-3439, Sept. 1976.

8. Twisdale, T., Tracking Task Maneuvers for Handling Qualities Evaluation, AFFTC TD75-1.

QUESTIONS AND ANSWERS

Lt. Crombie, AFFDL: Are your numerator criteria then dependent on the pilot model chosen?

Answer: No. There was no pilot "model" involved. We merely studied the time traces to identify what technique the pilots were employing.

Dr. Beam: I suggest you relate this criteria to how well a pilot can balance a rod on his finger. Do you think they would be the same?

Answer: To a certain extent they are related in that both tasks involve an attempt to control an unstable element. The difference is that the rod balance is an unstable element which the "pilot" must stabilize or lose. In our case here, the open-loop vehicle can be stable and the pilot drives it unstable because of the RHP zeros. If the pilot relaxes and lowers his gain the system returns to a stable condition. Thus, this criterion is not how much can the pilot balance (rod) but how far is he willing to push the instability.

Don Berry, NASA/Dryden: In the early part of your paper you showed two pilots giving the same configuration different departure susceptibility ratings. How does the use of the right half plane roll zero criteria give improved correlation for these cases?

Answer: The pilots gave ratings based upon the consequences of pressing to higher angles of attack and increasing instability levels. One pushed further into the instability region than the other and therefore saw a different susceptibility level. We merely determined how far the root had moved into the RHP at the time the pilot initiated recovery and compared this to his assessment of departure. It gave a better correlation because we were relating the pilot rating to what he saw at the instant he gave up.

C. Chalk: In earlier STI work a longitudinal parameter was proposed as a measure of departure tendency. What happened to this idea?

Answer: The longitudinal parameter is a similar right half plane zero but in the θ numerator which results from lateral/longitudinal coupling due to sideslip. It was shown in a previous program to contribute to a nose slice divergence because of closed-loop longitudinal control activity. This same phenomenon was present in this study; sideslip produced coupling between the longitudinal and lateral-directional axes which aggravated the nose slice tendency.

R. Woodcock, AFFDL/FGC: Can you clarify the implication of two findings from yaw simulation? First, your resistant/susceptible boundary seems independent of $Cn_{\beta_{dyn}}$. Second, the Weissman criteria seem valid except for being slightly conservative.

Answer: It is highly desirable that $Cn_{\beta_{dyn}}$ be positive because of open-loop stability considerations; however, it is not a requirement for closed-loop stability. The situations rated departure resistant involved recovery initiation at $Cn_{\beta_{dyn}}$ as low as -0.0005 and as high as $+0.002$ but always with $1/T_{\varphi_1} < 0.5$.

Regarding Weissman's criteria, the simulation results supported his boundaries for $Cn_{\beta_{dyn}} > 0$, but I would say it shows his criteria to be a bit optimistic for $Cn_{\beta_{dyn}} < 0$ in that it then allows a larger value of $1/T_{\varphi_1}$. Our results do not support this distinction, as noted above.

We did obtain a correlation for one pilot between his perception of increasing departure severity and decreasing $Cn_{\beta_{dyn}}$.

Transport Aircraft Flying Qualities Research*

by
W. W. Rickard**
and
D. S. Joshi**

Douglas Aircraft Company
McDonnell Douglas Corporation
Long Beach, California 90846

INTRODUCTION

The ability to accurately estimate the flying qualities of an airplane which exists only on paper is essential to the aerodynamic, control system, and autopilot design processes. Many criteria exist for estimating flying qualities, of which the best example is MIL-F-8785B. Unfortunately, this is a military flying qualities specification, containing criteria developed primarily on the basis of research and design experience on military aircraft. The criteria in MIL-F-8785B can be applied to all types of aircraft, from the smallest trainer to the largest transport. However, there are much less data to support the criteria for large transport (Class III) airplanes than there are for fighter/attack/interceptor (Class IV) airplanes. Designers of civil transport aircraft tend to doubt or even disbelieve the validity of some of the criteria (e.g., the lower limit on short-period frequency). Further, civil aircraft tend to have missions which are quite different from those of military aircraft, which suggests that different performance standards would apply. This is not to say that the military criteria are not used; however, they have certain shortcomings when applied to civil transport design.

A more serious criticism of most existing criteria is rooted in the fact that they are based on approximations to the response of an airplane. Examples of this are seen in the MIL-F-8785B criteria for the short period. These criteria are based on experimental data for which the short period is well damped and well separated from the phugoid. The current trend toward relaxed static stability airplanes with stability and control augmentation is gradually eroding the ability of such criteria to accurately predict flying qualities, especially for failure cases. There is a trend toward the use of pilot-model-in-the-loop criteria which place performance standards on the pilot plus airplane system, rather than on the airplane alone. At this time, however, no closed-loop criteria have been accepted for inclusion in MIL-F-8785B.

For these reasons, Douglas Aircraft Company has undertaken a program of research in the area of transport aircraft flying qualities. The goal of this research program is the determination of flying qualities criteria for the design of conventional as well as relaxed static stability airplanes. The work being done to develop flying qualities criteria for large transport aircraft in the landing approach is described in this paper.

Two transport aircraft research programs are summarized. The paper covers the program in two parts. Part 1 describes a lateral-directional study not previously reported in the open literature. Part 2 is a condensation of Douglas Paper 6496, which was presented in 1976 at the Twelfth Annual Conference on Manual Control, University of Illinois, Urbana, Illinois.

PART 1. LATERAL-DIRECTIONAL STUDY

ABSTRACT

A piloted motion-base simulator test was performed to study lateral-directional flying qualities criteria. Sixteen configurations were designed to span the spectrum of a number of lateral-directional parameters. All had the same longitudinal flying qualities, which were level 1. The criteria studied were all taken from MIL-F-8785B. Each is listed below by paragraph number and name. Only those preceded by an asterisk are discussed. The others are not discussed because they add nothing to the estimates of flying qualities.

*3.3.1.1	Dutch roll mode
3.3.1.2	Roll mode
3.3.1.3	Spiral mode
3.3.1.4	Coupled roll-spiral mode
3.3.2.2	Roll rate oscillations
*3.3.2.2.1	Roll rate oscillations for small inputs
*3.3.2.3	Bank angle oscillations
3.3.2.4	Sideslip excursions
*3.3.2.4.1	Sideslip excursions for small inputs
*3.3.4	Roll control effectiveness

The results of the test have been analyzed and conclusions drawn. The roll control effectiveness criterion (No. 3.3.4 of MIL-F-8785B) was found to be far too conservative. The other criteria were marginally substantiated by the data of this test.

OBJECTIVE

The primary objective of this project was to evaluate the lateral-directional criteria of MIL-F-8785B (References 1-1 and 1-2) for large transport aircraft in a landing approach configuration. The existing lateral-directional criteria have been found to be inadequate (References 1-3 and 1-4). Therefore, there is a need to test the validity of the lateral-directional MIL-F-8785B criteria and recommend necessary changes.

---

*This document presents the results of several projects performed under Douglas Independent Research and Development (IRAD) sponsorship.

**Senior Engineer, Aerodynamics Stability and Control Group.

APPROACH

Sixteen aircraft configurations were chosen to span the spectrum of each of five lateral-directional criteria (Dutch roll, roll rate oscillations, bank angle oscillations, sideslip excursion, and roll control effectiveness). These configurations, along with the MIL-F-8785B boundaries, are shown in Figures 1-1 through 1-4 and Table 1-1. In order to evaluate their flying qualities, these aircraft configurations were simulated on the Douglas motion-base simulator with human pilots in the control loop. The pilots were required to fly a constant altitude localizer tracking task until the glideslope was intercepted. The pilots were then required to track localizer and a 3-degree glideslope using the ILS. The simulation was terminated at touchdown. The landing approach geometry is shown in Figure 1-5 and the simulator control box is shown in Figure 1-6.

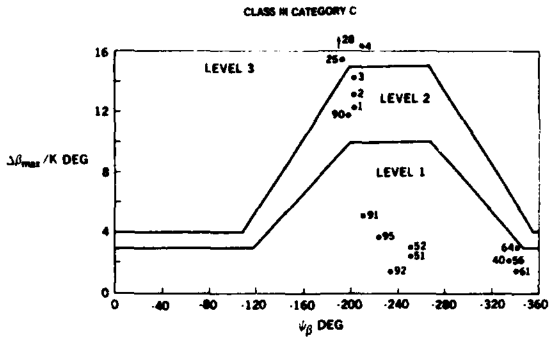


FIGURE 1-4. SIDESLIP EXCURSIONS

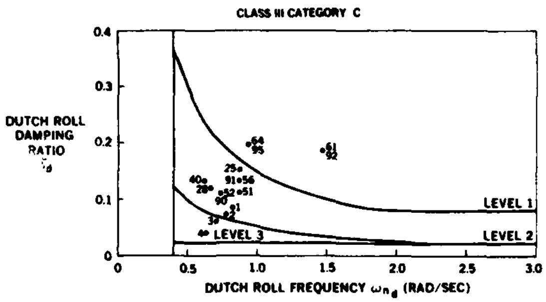


FIGURE 1-1. DUTCH ROLL MODE

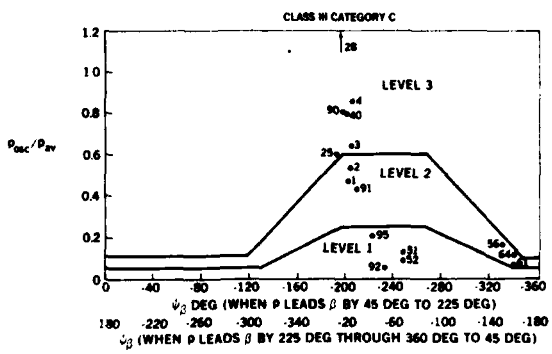


FIGURE 1-2. ROLL RATE OSCILLATIONS

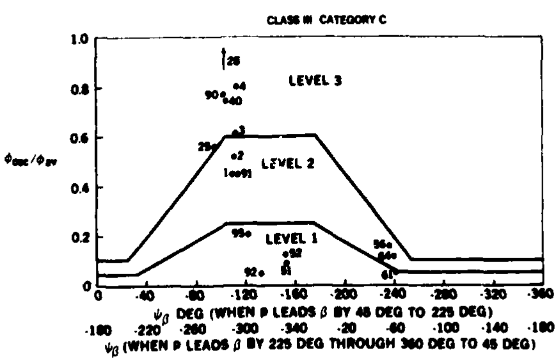


FIGURE 1-3. BANK ANGLE OSCILLATIONS

TABLE 1-1
ROLL PERFORMANCE REQUIREMENTS
CLASS III

FLIGHT PHASE CATEGORY	LEVEL 1	LEVEL 2	LEVEL 3
A	ϕ_t = 30 DEG IN 1.5 SEC	ϕ_t = 30 DEG IN 2.0 SEC	ϕ_t = 30 DEG IN 3.0 SEC
B	ϕ_t = 30 DEG IN 2.0 SEC	ϕ_t = 30 DEG IN 3.0 SEC	ϕ_t = 30 DEG IN 4.0 SEC
C	ϕ_t = 30 DEG IN 2.5 SEC	ϕ_t = 30 DEG IN 3.2 SEC	ϕ_t = 30 DEG IN 4.0 SEC

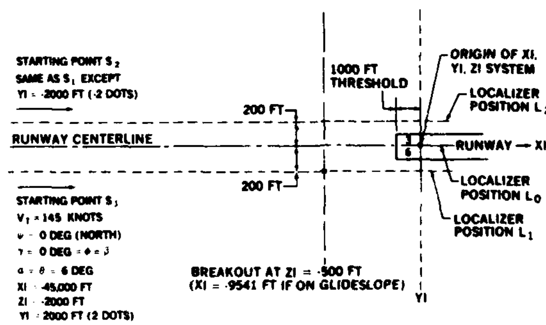


FIGURE 1-5. LANDING APPROACH GEOMETRY

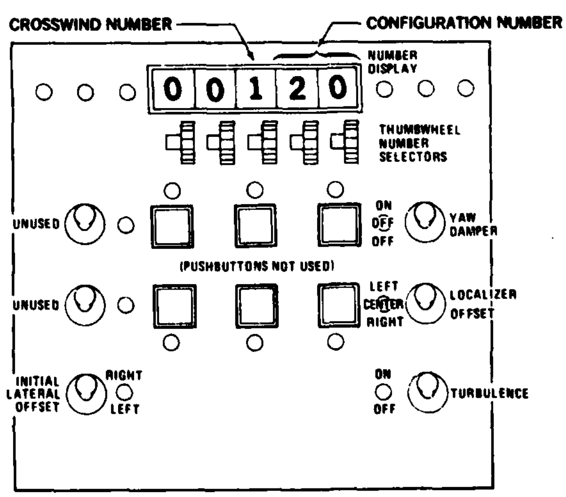


FIGURE 1-6. SIMULATOR CONTROL BOX

The test engineer sat in the right seat and the subject pilot in the left seat. The test engineer could select the task variables for each run using the control box. Because there were no oral requests for task variables as in previous tests, the pilot was unaware of the variables, such as wind, localizer offset, and starting point, at the start of the run. At the conclusion of each 3- to 4-minute flight, the pilots rated the overall flying qualities of the aircraft configuration using the Cooper-Harper pilot rating scale. Each evaluation was made with no turbulence and with light-to-moderate atmospheric turbulence. The pilot-opinion ratings have been tabulated and statistically analyzed.

ANALYSIS

The mean and standard deviations of the pilot ratings are shown in Figure 1-7 along with the MIL-F-8785B boundaries for the Dutch roll criterion. For the 16 configurations chosen, the boundaries separating the three levels are hyperbolic (Figure 1-1). These boundaries have been mapped as rectangular regions in Figure 1-7. Mathematically, these boundaries are:

$\zeta_d\omega_{n_d} \geqslant 0.15$	level 1
$0.05 < \zeta_d\omega_{n_d} < 0.15$	level 2
$\zeta_d\omega_{n_d} < 0.05$	level 3

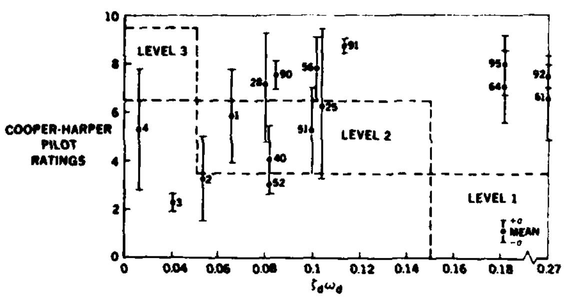


FIGURE 1-7. DUTCH ROLL CRITERION

Similar plots of pilot rating versus the criterion parameter have been made for the roll rate oscillation (3.3.2.2.1), bank angle oscillation (3.3.2.3), sideslip excursion (3.3.2.4), and roll control effectiveness (3.3.4) criteria. They are shown in Figures 1-8 through 1-11.

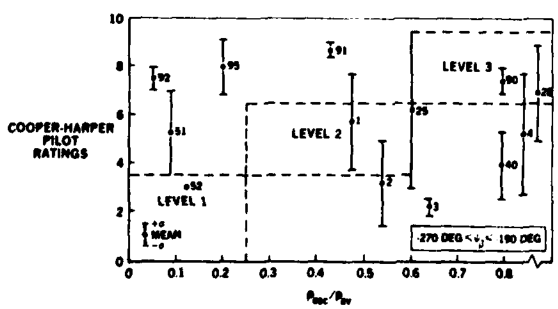


FIGURE 1-8a. ROLL RATE OSCILLATIONS

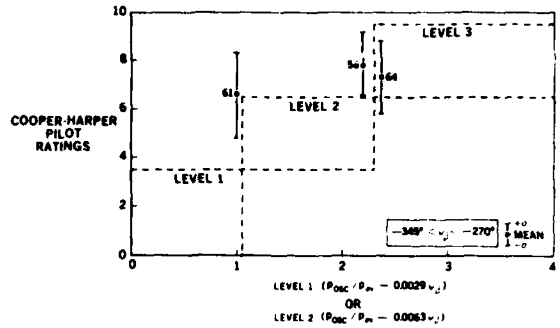


FIGURE 1-8b. ROLL RATE OSCILLATIONS

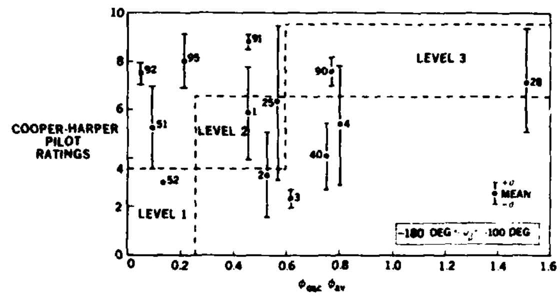


FIGURE 1-9a. BANK ANGLE OSCILLATIONS

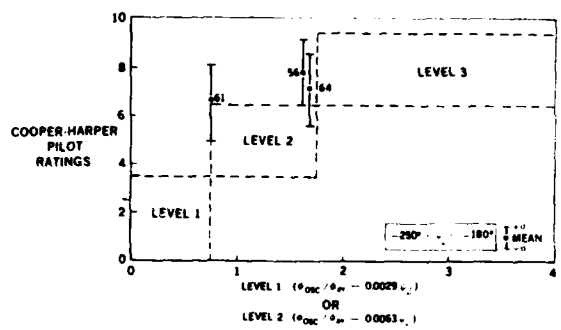


FIGURE 1-9b. BANK ANGLE OSCILLATIONS

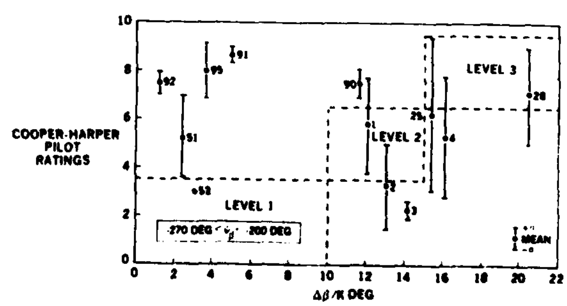


FIGURE 1-10a. SIDESLIP EXCURSIONS

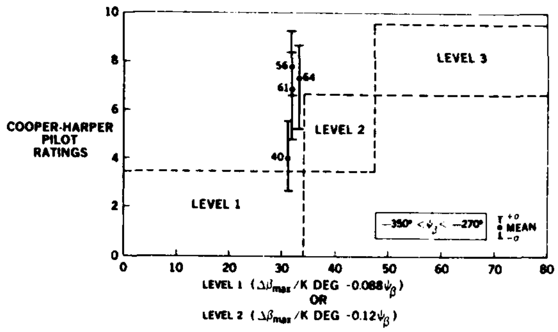


FIGURE 1-10b. SIDESLIP EXCURSIONS

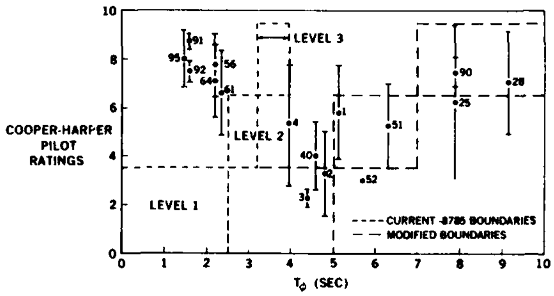


FIGURE 1-11. ROLL CONTROL EFFECTIVENESS

The flying qualities characteristics of the 16 configurations for the five criteria considered are given in Table 1-2, along with the pilot ratings. These are the average values of all ratings, both with and without turbulence, given by all pilots for each configuration. The flying qualities levels corresponding to these parameter values are given in Table 1-3, labeled as criteria I to V. Since there are five flying qualities estimates (one for each of the five criteria) for each configuration, one must decide how to combine these to estimate the overall flying qualities of a configuration. The specification provides no guidance in this area, but the accepted practice is to assume that the overall flying qualities will be as bad as, or worse than, the worst of the estimates. Thus, the worst estimate for a given configuration is shown as criterion VII. For reasons which will be explained later, the worst of I through IV (V is excluded) is shown to be the summary criterion, No. VI.

TABLE 1-2

CHARACTERISTICS OF THE CONFIGURATIONS

CONFIGURATION NUMBER	MEAN PILOT RATING	ω_d (RAD SEC)	ζ_d	$\omega_d \zeta_d$ (RAD SEC)	P_{osc}/P_{av}	ϕ_{osc}/ϕ_{av}	$\Delta\beta_{max}/k$ (DEG)	ψ_β (DEG)	$\psi_{p/\beta}$ (DEG)	T_ϕ (SEC)
1	5 79	0 825	0 080	0 066	0 478	0 451	12 20	205	145	5 1
2	3 25	0 763	0 069	0 053	0 552	0 521	13 10	206	132	4 8
3	2 25	0 706	0 059	0 041	0 649	0 612	14 20	206	137	4 4
4	5 31	0 634	0 043	0 027	0 853	0 802	16 30	207	143	4 05
25	6 25	0 879	0 154	0 135	0 594	0 567	15 40	196	117	7 9
28	7 12	0 661	0 122	0 081	1 510	1 452	23 80	193	133	9 2
40	4	0 630	0 130	0 082	0 798	0 747	20 91	202	131	4 6
51	5 25	0 861	0 118	0 102	0 092	0 088	2 36	250	133	6 3
52	3	0 744	0 112	0 083	0 132	0 126	2 98	250	138	5 7
56	7 83	0 852	0 134	0 114	0 164	0 158	1 97	25	180	2 7
61	6 58	1 471	0 182	0 268	0 056	0 054	1 35	18	175	2 3
64	7 1	0 913	0 199	0 182	0 117	0 114	2 96	17	175	2 2
90	7 5	0 744	0 112	0 083	0 794	0 772	11 70	200	133	7 9
91	8 75	0 852	0 134	0 114	0 456	0 449	4 97	211	132	1 6
92	7 5	1 471	0 182	0 268	0 054	0 049	1 33	235	109	1 6
95	8	0 913	0 199	0 182	0 213	0 210	3 67	225	124	1 5

TABLE 1-3

FLYING QUALITIES OF THE CONFIGURATIONS

CONFIGURATION NUMBER	MEAN PILOT RATING	PILOT RATING LEVEL	FLYING QUALITIES LEVELS $\omega_d \zeta_d$ I	P_{osc}/P_{av} II	ϕ_{osc}/ϕ_{av} III	$\Delta\beta_{max}/k$ IV	T_ϕ V	MAX OF I TO IV VI	MAX OF I TO V VII
1	5 79	2	2	2	2	2	X	2	X
2	3 25	1	2	2	2	2	X	2	X
3	2 25	1	3	3	3	2	X	3	X
4	5.31	2	3	3	3	3	3	3	3
25	6 25	2	2	3	3	3	X	3	X
28	7 12	3	2	3	3	3	X	3	X
40	4	2	2	3	3	1	X	3	X
51	5.25	2	2	1	1	1	X	2	X
52	3	1	2	1	1	1	X	2	X
56	7.83	3	2	2	2	1	1	2	2
61	6 58	3	1	2	1	1	1	2	2
64	7 1	3	1	2	2	1	1	2	2
90	7 5	3	2	3	3	2	X	3	X
91	8.75	3	2	2	2	1	1	2	2
92	7 5	3	1	1	1	1	1	1	1
95	8	3	1	1	1	1	1	1	1

NOTE THE LETTER X MEANS WORSE THAN LEVEL 3

A number of other criteria were examined but are not presented here because they add nothing to the study. For example, all 16 configurations were rated level 1 by the roll mode, spiral mode, and coupled roll-spiral mode criteria. These results are not shown because they add no useful information.

Table 1-4 shows the difference between the pilot opinion rating and the MIL-F-8785B boundaries for each of the five lateral-directional criteria. This table was derived from Figures 1-7 through 1-11 by calculating the difference between the mean ratings and the nearest level boundary (dotted horizontal line). Thus, positive ΔPR means that the pilot ratings are higher (worse) than the expected MIL-F-8785B boundary. Similarly, a negative ΔPR indicates that the pilots have rated this configuration better (lower rating) than MIL-F-8785B. A zero in this table, therefore, means that the pilot ratings are within the levels predicted by MIL-F-8785B. The accepted practice, as stated above, for obtaining overall configuration characteristics is to take the worst estimate as the overall rating. Thus, the smallest number in a given row in Table 1-4 represents the overall estimated flying qualities. The specification has given the correct result if the smallest number in a row is zero or near zero. If the smallest number in a row is negative, the estimate is conservative, and if positive, the estimate is unconservative. The data for criteria VI and VII are plotted in Figure 1-12.

TABLE 1-4

DIFFERENCES BETWEEN PILOT RATING AND MIL-F-8785B CRITERIA BOUNDARIES

CONFIGURATION NUMBER	MEAN PILOT RATING	DIFFERENCES BETWEEN PR AND 8785B BOUNDARIES ΔPR $\omega_d \zeta_d$ I	P_{osc}/P_{av} II	ϕ_{osc}/ϕ_{av} III	$\Delta\beta_{max}/k$ IV	T_ϕ V	MIN OF I TO IV VI	MIN OF I TO V VII
1	5 79	0	0	0	0	3 75	0	3 75
2	3 25	0 25	0 25	0 25	0 25	6 25	0 25	6 25
3	2 25	4 1	4 25	1 25	1 25	7 25	4 25	7 25
4	5 31	1 75	1 25	1 25	1 25	1 25	1 25	1 75
25	6 25	0	0	0	0 25	3 25	0 25	3 25
28	7 12	0 6	0	0	0	2 25	0	2 25
40	4	0	2 5	2 5	0 5	5 5	2 5	5 5
51	5 25	0	1 75	1 75	1 75	4 12	0	4 25
52	3	0 5	0	0	0	6 5	0 5	6 5
56	7 83	1 25	1 75	1 25	4 25	4 25	1 25	1 25
61	6 58	3 1	3 0	0 1	3 0	3 0	0 1	0 1
64	7 1	3 6	1 75	0 75	1 25	3 75	0 75	0 75
90	7 5	1 0	0	0	1 0	2	0	2
91	8 75	2 25	2 25	2 25	5 25	5 25	2 25	2 25
92	7 5	4 0	4 0	4 0	4 0	4	4 0	4 0
95	8	4 5	4 5	4 5	4 5	4 5	4 5	4 5

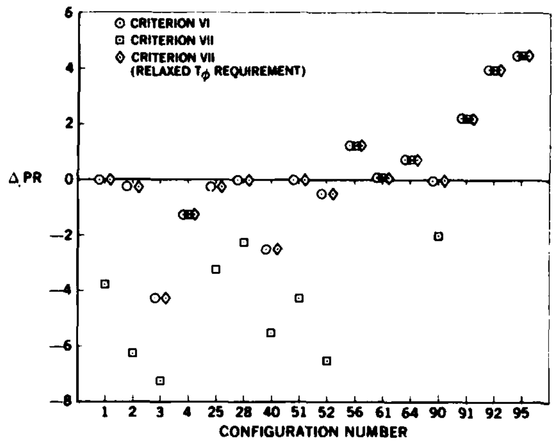


FIGURE 1-12. DIFFERENCES BETWEEN ESTIMATED AND ACTUAL FLYING QUALITIES

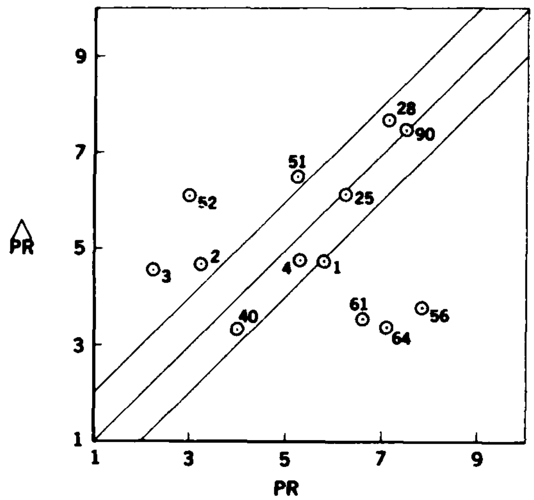


FIGURE 1-13. COMPARISON OF PILOT RATINGS FROM REGRESSION TO ACTUAL RATINGS

Table 1-5 shows the correlation coefficient between the subjective pilot ratings and each of the lateral-directional parameters. Regression coefficients were not calculated, as it seemed unlikely that any one parameter would be a reasonable predictor of pilot rating. The correlation coefficient, r, was calculated using the following equation:

$$r = \frac{N\Sigma X_i Y_i - (\Sigma X_i)(\Sigma Y_i)}{\sqrt{(N\Sigma X_i^2 - (\Sigma X_i)^2)(N\Sigma Y_i^2 - (\Sigma Y_i)^2)}} \qquad (1)$$

where X_i = any one of

$(\zeta_d\omega_{n_d}, p_{osc}/p_{av}, \phi_{osc}/\phi_{av}, \Delta\beta_{max}/k, \psi_{\beta_{step}})$

Y_i = corresponding opinion ratings

N = number of data points

In addition, a multiple regression analysis was conducted to predict the pilot opinion ratings as a linear function of $1/\zeta_d\omega_{n_d}$, p_{osc}/p_{av}, ϕ_{osc}/ϕ_{av}, $\Delta\beta_{max}/k$ and T_ϕ. The following equation defines this relationship:

$$\hat{PR} = 0.032/\zeta_d\omega_{n_d} + 2.36\, p_{osc}/p_{av} - 0.2\,\Delta\beta_{max}/k + 0.7T_\phi + 1.97 \qquad (2)$$

TABLE 1-5

LINEAR REGRESSION CORRELATION COEFFICIENT

	$\zeta_d\omega_d$	p_{osc}/p_{av}	ϕ_{osc}/ϕ_{av}	$\Delta\beta_{max}/k$	T_ϕ	ψ_β
CORRELATION COEFFICIENT	0.37	0.14	0.15	0.31	0.17	0.19

The variable ϕ_{osc}/ϕ_{av} does not enter the regression due to its high correlation ($r = 1$) with p_{osc}/p_{av}. A comparison of the true pilot ratings (PR) and ratings estimated by this model ($\hat{PR}$) are presented in Figure 1-13.

DISCUSSION OF RESULTS

Four of the five MIL-F-8785B criteria ($\zeta_d\omega_{n_d}$, p_{osc}/p_{av}, ϕ_{osc}/ϕ_{av}, and $\Delta\beta_{max}/k$) estimated level 2 flying qualities for configuration 1. The mean pilot rating (5.8) for this configuration agrees with these estimates. The roll control criterion, however, predicts worse than level 3 flying qualities. This is a very conservative estimate. The pilot ratings for configuration 2 show good agreement (*ΔPR = -0.25) with four of the five* criteria. The fifth criterion, roll control effectiveness, was again extremely conservative (ΔPR = -6.25).

The estimates for configuration 3 were poor, with the roll control criterion more than two levels worse and the Dutch roll mode and roll rate oscillations criteria more than one level worse. The roll and sideslip angle oscillation criteria were worse by only about 1-1/4 units on the pilot rating scale, but this is immaterial – the judging rules say only the worst estimate counts. All five criteria give the same slightly conservative estimate for configuration 4. The inconsistency is 1-1/4 units which is within the level of experimental error. Throughout this discussion, the word "units" refers to units of pilot opinion rating while "level" refers to flying qualities levels.

The first four criteria gave correct estimates for configurations 25 and 28, while the roll control criterion was worse by about a full level. The Dutch roll and sideslip excursion criteria accurately predicted the flying qualities of configuration 40. On the other hand, the roll rate and the bank angle oscillation criteria estimated flying qualities that were 2-1/2 units worse than the pilot ratings. In addition, the roll control criterion was worse by more than one level.

The criteria again gave nearly the correct flying qualities estimate for configuration 51 if the roll control criterion, which was worse by more than a level, was neglected. The same result was found for configuration 52, except that the roll control criterion was much worse. The specification criteria as a whole mispredicted the flying qualities of configuration 56 by only 1-1/4 units, with Dutch roll mode and bank angle oscillations equally critical. The estimated flying qualities of configuration 61 also match the true flying qualities (pilot opinion), although only bank angle oscillations are critical. The estimate for configuration 64 is almost as good, with two criteria only about one unit better than estimated. The other three are about a level off, but predict better flying qualities and can be ignored. The estimates for configuration 90 are also good, except that the roll control criterion estimates two units worse than the true flying qualities. This is somewhat more than one would attribute to experimental error.

Configurations 91, 92, and 95 are qualitatively different from the rest in that the estimates are substantially better than the actual flying qualities. While configuration 91 has level 3 flying qualities, three criteria (Dutch roll mode and roll rate and bank angle oscillations) estimate level 2 and the other two level 1. The estimates for configurations 92 and 95 are all level 1, although the actual flying qualities are level 3. No explanation has been found for this anomaly.

It seems clear at this point that the roll control criterion is much too stringent. A need to relax this criterion can be further demonstrated by comparing criteria VI and VII of Figure 1-13. Criterion VI is a measure of how effective the first four MIL-F-8785B criteria are in estimating the true flying qualities. Criterion VII, in addition, includes the roll control effectiveness criterion. A comparison of these criteria shows that 10 of the 16 configurations have flying qualities one to two levels better than criterion VII predicts. Moving the level 1 boundary from 2.5 to 5.0 seconds, the level 2 boundary from 3.2 to 7.0 seconds, and the level 3 boundary from 4.0 to 9.0 seconds would dramatically improve the estimates for configurations 1, 2, 3, 25, 28, 40, 51, 52, and 90. The poor characteristics of configurations 4, 56, 61, and 64 would still be predicted by other criteria. None of the criteria predict the characteristics of configurations 91, 92, and 95, with or without this change. Figure 1-12 shows the flying qualities levels and the differences between the pilot ratings and the MIL-F-8785B boundaries with the relaxed T_ϕ requirement. A comparison of criteria VI and VII in this figure indicates that the relaxed T_ϕ criterion results are consistent with the rest of the experiment. This change, however, will *not* be recommended at this time as the data are not considered adequate to support such a substantial change. References 1-3 and 1-4 have suggested relaxing the level 1 MIL-F-8785 boundaries from 2.5 to 3.5 seconds.

No other clear-cut discrepancy between the specification criteria and these experimental data was found. Configurations 1, 2, 3, and 4 were designed to explore the level 2-3 boundary on Dutch roll characteristics, but the results were inconclusive. Configuration 1, which should have gotten the best rating in this group of four, got the worst rating. Configuration 2 was rated slightly better than expected, configuration 3 much better, and configuration 4 slightly better. No change could be made in any boundary to cause the criteria to be consistent with the pilot ratings. Configuration 40 was also rated substantially better than expected. The bad estimate was produced by the roll rate and attitude oscillation criteria. No explanation was found for this anomaly.

The estimates were unconservative for configurations 56, 61, and 64, but the discrepancies were 1.25, 0.10, and 0.75 units, respectively. These are within an acceptable level of experimental error.

The correlation coefficients between the subjective pilot opinion ratings and the lateral and directional flying quality parameters are presented in Table 1-5. The correlation coefficient is a statistical measure of how accurately a linear variation defines the relation between two parameters. There is a reasonable correlation between the pilot opinion ratings and the Dutch roll mode ($r = 0.37$) and sideslip excursions ($r = 0.31$). This means that the pilot response can be predicted, though not very well, by a linear function of the Dutch roll or the sideslip excursion parameter. The multiple linear regression model (Equation 2) was calculated by discarding configurations 91, 92, and 95. Based on the physics of the problem, two fictitious configurations were included to bias the data. Despite the fact that the regression equation does not accurately predict the true pilot ratings, the regression coefficients accurately model the physical problem. The square of the multiple correlation coefficient (R) is a true measure of how well the fitted equation explains the variations in the data (Reference 1-5).

$$R^2 = \frac{\text{sum of squares due to regression}}{\text{total corrected sum of squares}} = 0.56$$

This means that only 56 percent of the variation in the data is explained by this model. The correlation coefficient has the value 0.75, which is substantially better than any of the values in Table 1-5.

CONCLUSIONS AND RECOMMENDATIONS

In order to evaluate the existing lateral-directional flying qualities of MIL-F-8785B, 16 aircraft configurations were tested on a motion base simulator with a pilot in the control loop. This is a complex problem because several variables govern the lateral-directional handling qualities. Further complications arise due to the fact that the subjective opinion of a human operator, in most cases, is not easy to quantify. However, an attempt has been made in this report to analyze and interpret the pilot opinion ratings. The following preliminary conclusions have been drawn:

1. The estimated flying qualities of an airplane configuration can be obtained from a set of criteria as the worst of the estimates. The ratings given by the pilots are considered the true measure of flying qualities. The estimates, as defined above, should tend toward the true values.

2. In terms of correlation coefficients, the Dutch roll parameter ($\zeta_d \omega_{n_d}$) was the most significant factor in determining the flying qualities of the configurations in this experiment. The sideslip oscillation parameter ($\Delta\beta_{max}/k$) was nearly as significant. The other parameters (p_{osc}/p_{av}, ϕ_{osc}/ϕ_{av}, T_ϕ, and ψ_β) were substantially less significant.

3. Based on this experiment, the sharp corner boundaries of MIL-F-8785B for the p_{osc}/p_{av}, ϕ_{osc}/ϕ_{av}, and $\Delta\beta_{max}/k$ criteria are inadequate. No revision can be proposed on the basis of this experiment. Further research is needed.

4. A complete revision of the roll control effectiveness criterion is needed. To be consistent with the data of this experiment, the level 1 boundary should be changed from 2.5 to 5.0 seconds, the level 2 boundary from 3.2 to 7.0 seconds, and the level 3 boundary from 4.0 to 9.0 seconds. While the MIL-F-8785B boundaries are too conservative, these changes are unconservative and will not be recommended. Further research is required to properly define these boundaries.

5. With the exception of roll control effectiveness, the MIL-F-8785B criteria predictions of flying qualities are marginally substantiated by the data of this test.

REFERENCES

1-1. Anonymous. Flying Qualities of Piloted Airplanes. MIL-F-8785B, August 1969.

1-2. Chalk, C. R., et al. Background Information and User Guide for MIL-F-8785B, Flying Qualities of Piloted Airplanes. AFFDL-TR-69-72, August 1969.

1-3. Holleman, E. C., and Gilyard, G. B. In-Flight Evaluation of the Lateral Handling of a Four-Engine Jet Transport During Approach and Landing. NASA TN-D-6339, May 1971.

1-4. Ashkenas, I. L. A Study of Conventional Airplane Handling Qualities Requirements, Part 1 – Roll Handling Qualities. Technical Report AFFDL-TR-65-138, November 1965.

1-5. Draper, N. R., and Smith, H. Applied Regression Analysis. John Wiley and Sons, New York, 1966.

PART 2. LONGITUDINAL STUDY

ABSTRACT

An investigation of the longitudinal flying qualities of large transport aircraft in the landing approach was performed as a portion of a long-range flying qualities independent research and development program at Douglas Aircraft Company. A literature study was performed to gather all criteria which showed promise as estimators* of flying qualities. Then a piloted motion base simulator experiment was conducted to produce data which could be used to evaluate the selected criteria. Each criterion was evaluated by comparing the estimated flying qualities it produced for each configuration with the Cooper-Harper ratings given by the pilots. An appraisal was then made of each criterion based on its performance in this study. The criteria evaluated included several from MIL-F-8785B (Reference 2-1) (flightpath stability, short period frequency, short period damping ratio, phugoid stability, and static stability), the short-period criterion of SAE ARP 842B (Reference 2-2), the short-period criterion of Reference 3, and a pitch tracking task criterion (References 2-4 and 2-5). The best results were obtained by combining the information contained in the flight path stability and pitch tracking task criteria.

DISCUSSION OF LONGITUDINAL FLYING QUALITIES CRITERIA SELECTED FOR INVESTIGATION

The first stage of the program of research was a wide-ranging review of the literature for longitudinal flying qualities criteria. There are far too many criteria in existence to be tested in an experimental program or to be discussed in detail here. A relatively small number which showed promise or which are generally accepted were selected for inclusion in this flying qualities experiment. The criteria of MIL-F-8785B were included because they are "accepted" criteria. The short-period criterion of ARP 842B was included as an "accepted" criterion in civil aircraft design. The short-period criterion of Reference 2-3 was included because it contains, in a single criterion, the information provided by several other criteria. Finally, a pilot-model-in-the-loop pitch tracking task criterion which had shown promise in earlier studies was included.

*The term "estimators" is used because the criteria produce quantitative estimates of flying qualities (i.e., pilot ratings or flying qualities levels)

DESIGN OF THE EXPERIMENT

A flying qualities experiment was designed to provide data for evaluation of the selected flying qualities criteria. The criteria are as follows: static stability, $d\gamma/dV$, $\omega_{n_{SP}}$, ζ_{SP}, n/α, $\omega_{n_{PH}}$, ζ_{PH}, phase compensation, and resonance. Two approaches were used to design two groups of configurations. The 26 configurations of the first group are either typical wide-body airplanes with cg locations from far forward to far aft of the neutral point, or such airplanes with a single stability derivative varied to change the flying qualities. The characteristics of these configurations are given in Table 2-1. The configurations of Group II, on the other hand, were obtained by specifying the characteristics given in Table 2-2, and solving for the equations of motion coefficients. The solution to this transformation is not unique, as there are more than twice as many unknowns as there are conditions. A computer program was written to solve this transformation on the basis of minimizing a weighted sum of squared errors between the specified values of the parameters and the values calculated for a trial set of equations of motion constants. The algorithm exhibited poor convergence properties in general, and in particular for $\zeta_{Ph} < 0.04$. However, several hundred configurations were calculated for which the algorithm converged. The 16 configurations of Group II were selected from these.

TABLE 2-1

GROUP I CONFIGURATION CHARACTERISTICS

V = 140 KN γ = 3° W = 350,000 LB

	$\omega_{n_{SP}}$	ζ_{SP}	$\omega_{n_{Ph}}$	ζ_{Ph}	n/α	$d\gamma/dV$	$1/T_{\theta_1}$	$1/T_{\theta_2}$
1	0.846	0.628	0.186	0.072	3.80	-0.0399	-0.084	-0.506
2	0.732	0.708	0.169	0.063	3.94	-0.0432	-0.083	-0.528
3	(-0.633)	(-0.307)[1]	0.086	0.318	4.14	-0.0491	-0.082	0.556
4	(-0.811)	(+0.090)[2]*	0.200†	0.636†	4.20	-0.0511	0.082	-0.564
5	(-0.909)	(+0.158)[3]*	0.210†	0.479	4.24	-0.0530	-0.082	0.568
6	0.828	0.645	0.190	0.057	3.80	0.148	-0.013	0.577
7	0.819	0.653	0.192	0.049	3.80	0.236	+0.015	-0.605
8	0.811	0.662	0.194	0.041	4.04	0.339	+0.041	-0.631
9	0.804	0.565	0.188	0.084	2.75	0.0054	-0.102	-0.339
10	0.795	0.502	0.191	0.099	1.78	0.095	[0.166]	[0.917]
11	0.723	0.431	0.194	0.117	0.82	0.400	[0.143]	[0.587]
12	0.853	0.888	0.184	0.080	3.80	0.0399	-0.084	-0.531
13	0.836	0.337	0.188	0.066	3.80	-0.0399	-0.084	-0.481
14	0.829	0.149	0.189	0.064	3.80	-0.0399	-0.084	-0.466
15	(0.991)	(+0.225)[4]*	0.211†	0.388†	4.29	-0.0551	-0.082	0.575
16	(-1.061)	(+0.291)[5]*	0.210†	0.331†	4.35	-0.0572	0.082	0.583
17	(1.125)	(+0.358)[6]*	0.209†	0.295†	4.43	-0.0593	-0.081	0.595
18	0.953	0.570	0.165	0.107	3.65	0.0360	0.087	0.484
19	0.596	0.841	0.141	0.073	4.06	0.0465	0.082	-0.544
20	0.843	0.395	0.187	0.106	0.71	0.498	[0.141]	[0.545]
21	0.441	0.665	0.170	0.043	1.05	0.285	[0.149]	[0.676]
22	(-0.577)	(+0.152)[7]*	0.190†	0.347†	1.22	0.222	[0.154]	[0.731]
23	(-0.767)	(+0.341)[8]*	0.196†	0.240†	1.37	0.173	[0.158]	[0.776]
24	(-0.904)	(+0.499)[9]*	0.196	0.207	1.54	0.133	[0.163]	[0.828]
25	0.833	0.263	0.188	0.065	3.80	0.0340	0.084	-0.475
26	0.831	0.197	0.189	0.064	3.80	0.0340	0.084	-0.470

( ) FIRST ORDER FACTOR

[1] 0.441 (1.07 [illegible]   [4] τ_2 3.08   [7] τ_2 4.56

[2] τ_2 1.70   [5] τ_2 2.38   [8] τ_2 2.03

[3] τ_2 4.39   [6] τ_2 1.94   [9] τ_2 1.39

*TESTED AGAINST PHUGOID CRITERION

†TESTED AGAINST SHORT PERIOD CRITERION

TABLE 2-2

GROUP II CONFIGURATION CHARACTERISTICS

V = 140 KN γ = -3° W = 350,000 LB

CONFIG	ω_{SP}	ζ_{SP}	ω_{Ph}	ζ_{Ph}	n/α (g/rad)	dγ/dV (deg/kt)	$1/T_{\theta_1}$	$1/T_{\theta_2}$
27	1.39	0.50	0.16	0.12	2.42	0.1	0.0607	0.325
30	1.05	0.85	0.16	0.12	1.38	0.1	0.0335	0.179
39	(0.744)[1]	(2.585)[1]	0.16	0.28	2.61	0.1	0.0372	0.484
40	1.05	0.85	0.16	0.12	1.40	0.1	[0.127]	[0.940]
43	1.39	0.5	0.08	0.12	2.43	0.05	0.0534	0.293
49	1.05	0.5	0.08	0.12	1.40	0.1	0.0397	0.221
61	1.39	0.85	0.08	0.28	2.67	0.1	0.0428	0.555
62	1.05	0.85	0.08	0.12	1.45	0.1	0.0408	0.218
66	0.592	0.85	0.08	0.12	3.5	0.1	0.0681	0.380
75	(0.318)[2]	(1.10)[2]	0.16	0.28	3.5	0.1	-0.0471	0.808
76	0.592	0.85	0.08	0.28	3.5	0.05	0.0767	0.430
84	0.447	0.85	0.16	0.12	2.0	0.05	[0.181]	[0.944]
85	0.447	0.5	0.16	0.12	2.0	0.1	0.0494	0.272
90	0.592	0.5	0.08	0.12	3.5	0.05	0.0761	0.400
91	0.447	0.5	0.08	0.12	2.0	0.025	0.0860	0.458
96	1.05	0.5	0.08	0.12	1.46	0.1	[0.197]	[0.941]

[1] EQUIVALENT [illegible]

[2] EQUIVALENT [illegible]

PERFORMANCE OF THE EXPERIMENT

The configurations were rated by pilots flying the McDonnell Douglas six-axis motion base simulator located at Long Beach, California. The simulator, shown in Figure 2-1, is supported by six hydraulic jacks arranged in a configuration developed by the Franklin Institute. The limits of linear and rotary motion of this system are given in Table 2-3. Interior and exterior views of the simulator cockpit are shown in Figures 2-1 and 2-2. The airplane equations of motion are programmed on a hybrid computer system, of which the major elements are Xerox Sigma Five digital computer and a Comcor Astrodata Ci-5000 hybrid computer. Cockpit motion commands are generated in the hybrid system and transmitted to a DEC PDP 11/40 minicomputer. The minicomputer computes the geometric transformations and controls the hydraulic jacks in a closed-loop fashion, using LVDT transducer feedback from the jacks. Figure 2-3 is a schematic of the elements of the motion base simulator facility. The visual display is generated by a Redifon II system, using a detailed terrain model for landing approaches.

TABLE 2-3
MOTION LIMITS FOR THE MOTION BASE

MOTION	EXCURSION	VELOCITY	ACCELERATION
HEAVE	±116 cm (±46 IN.)	(±81 cm/SEC) (±32 IN./SEC)	±1.75 G
SWAY	±147 cm (±58 IN.)	±98 cm/SEC (±38.5 IN./SEC)	±1.45 G
SURGE	±152 cm (±60 IN.)	±98 cm/SEC (±38.5 IN./SEC)	±1.45 G
ROLL	±30°	±23°/SEC	6.9 RAD/SEC^2
PITCH	±30°	±23°/SEC	6.9 RAD/SEC^2
YAW	±30°	±30°/SEC	8.1 RAD/SEC^2

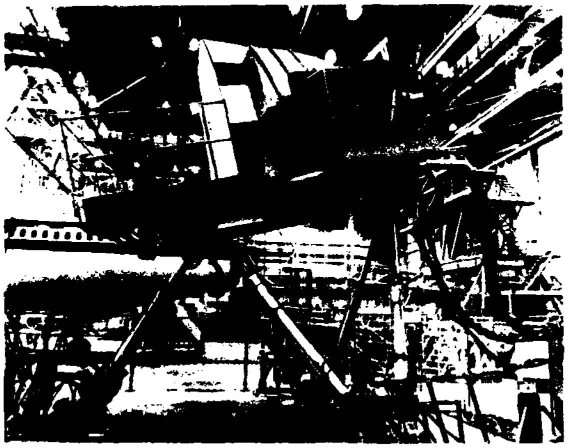


FIGURE 2-1. MOTION BASE SIMULATOR

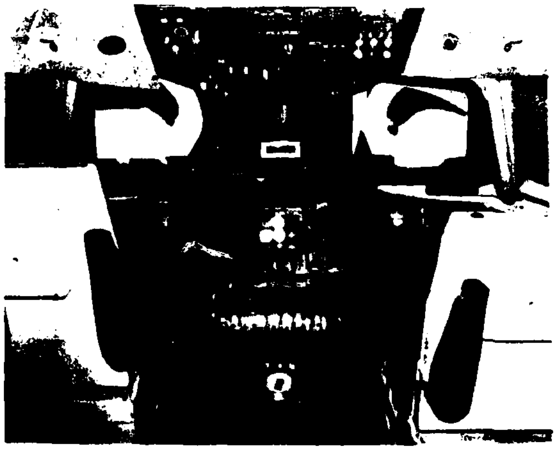


FIGURE 2-2. MOTION BASE SIMULATOR COCKPIT

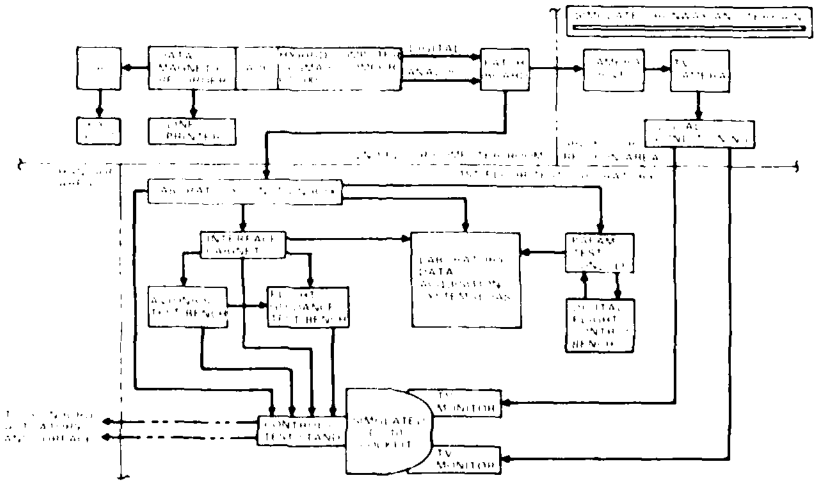


FIGURE 2-3. FIXED BASE SIMULATOR

Five Douglas Aircraft Company test pilots performed 154 evaluations of the 42 configurations over a period of 2 weeks. Each evaluation consisted of one to three ILS approaches, at the pilot's discretion, after which the pilot gave the configuration a pilot rating on the Cooper-Harper scale. The ILS approach began at a range of 13.7 kilometers (7.4 nautical miles) from the threshold, at an altitude of 457 meters (1500 feet), and on the extended runway centerline. The 3-degree glideslope was intercepted at a range of about 8.7 kilometers (4.7 nautical miles). The pilot then flew down the glideslope in a turbulent atmosphere. Lateral-directional dynamics typical of a wide-body transport were simulated but held constant throughout the experiment. After breakout at an altitude of 213 meters (700 feet), the pilot transitioned to the visual display for flare and touchdown. The simulation permitted the pilot to stop, turn, and taxi the airplane on the ground, but this was not part of the evaluation task. The test engineer, who rode in the copilot seat, recorded the pilot rating and pilot comments.

RESULTS AND ANALYSIS

The flying qualities criteria were evaluated by comparing the level of flying qualities predicted for a given configuration with the actual, or true, level of flying qualities for that configuration. The true level of flying qualities for each configuration was assumed to be represented by the average of the ratings that the pilots gave that configuration. The Cooper-Harper pilot rating scale used in this experiment is repeated here as Figure 2-4. The results of this experiment are given in Tables 2-4 and 2-5 for the Group I and II configurations, respectively. The first column in each of these tables lists the configurations by number. The next column gives the mean pilot rating for each configuration. The third column, labeled R_o, is the actual, or true, level of flying qualities for each configuration, based on the mean pilot rating. Every configuration in Group I was rated by at least three different pilots, some by four, and some by all five pilots. In Group II, one configuration was rated by

TABLE 2-4

GROUP I – COMPARISON OF CRITERIA

		R_0	R_1	R_2 (MIL-F-8785B)	R_3 (MIL-F-8785B)	R_4 (MIL-F-8785B)	R_5 (MIL-F-8785B)	R_6 (MIL-F-8785B)	R_8	R_9	R_{10}	R_{13}
CONFIG	PR	PR LEVEL	BANDWIDTH MODEL	$d\gamma/dV$ LEVEL	$\omega_{n_{SP}}$ VS n/α LEVEL	ζ_{SP} LEVEL	ζ_{Ph} OR T_2 LEVEL	STATIC STAB	ARP-842 $\omega_{n_{SP}}$ VS ζ_{SP}	$L_\alpha/\omega_{n_{SP}}$ VS ζ_{SP}	WORST OF R_2–R_6	$f(R_1, R_2)$
1	2.50	1	1	1	1	1	1	YES	1	1 1/2	1	1
2	2.20	1	1 1/2	1	2	1	1	YES	2	2	2	1 1/2
3	4.30	2	2	1	4	1	2	YES	3	3	4	2
4	3.93	1 1/2	2	1	4	1	4	NO	3	3	4	2
5	5.17	2	2 1/2	1	4	3	4	NO	3	3	4	2 1/2
6	5.00	2	1	2 1/2	1	1	1	YES	1	2	2 1/2	2
7	4.25	2	1	3 1/2	1	1	1	YES	1	2	3 1/2	2 1/2
8	8.33	3	1 1/2	4	1	1	1	YES	1	2	4	3
9	5.00	2	1	1 1/2	1	1	1	YES	1	1	1 1/2	1 1/2
10	5.67	2	1	2	1	1	1	YES	2	1	2	1 1/2
11	7.33	3	2 1/2	4	3	1	1	YES	2	1	4	3 1/2
12	4.00	2	1	1	1	1	1	YES	3	2	1	1
13	4.00	2	1 1/2	1	1	2	1	YES	2	2	2	1 1/2
14	7.00	3	3	1	1	3 1/2	1	YES	3	3	3 1/2	3
15	6.67	2 1/2	2 1/2	1	4	1	4	NO	3	3	4	2 1/2
16	7.67	3	3	1	4	2	4	NO	3	3	4	3
17	9.00	3	3	1	4	2	4	NO	3	3	4	3
18	3.75	1 1/2	1	1	1	1	1	YES	1	1	1	1
19	4.00	2	2	1	4	1	1	YES	2	3	4	2
20	8.00	3	3 1/2	4	3	1	1	YES	2	3	4	4
21	6.17	2 1/2	2	4	2	1	1	YES	2	1	4	3
22	6.33	2 1/2	2	3	4	1 1/2	4	NO	3	3	4	2 1/2
23	9.33	3 1/2	3	3	4	3	4	NO	3	3	4	3
24	9.33	3 1/2	3	2	4	3	4	NO	3	3	4	3
25	5.00	2	2	1	1	2	1	YES	2 1/2	3	2	2
26	5.67	2	2 1/2	1	1	3	1	YES	3	3	3	2 1/2
			25	50	57	47	59		34	34	51	17

TABLE 2-5

GROUP II – COMPARISON OF CRITERIA

		R_0	R_1	R_2 (MIL-F-8785B)	R_3 (MIL-F-8785B)	R_4 (MIL-F-8785B)	R_5 (MIL-F-8785B)	R_6 (MIL-F-8785B)	R_8	R_9	R_{10}	R_{13}
CONFIG	PR	PR LEVEL	BANDWIDTH MODEL	d_γ/dV LEVEL	$\omega_{n_{sp}}$ vs n/α	ζ_{SP} LEVEL	ζ_{Ph} OR T_2 LEVEL	STATIC STAB	ARP 842B	$L_\alpha/\omega_{n_{sp}}$ vs ζ_{sp} LEVEL	WORST OF R_2 R_6	$f(R_1, R_2)$
27	7.00	3	1 1/2	2	1	1	1	YES	1	3	2	2
30	4.75	2	1	2	1	1	1	YES	2 1/2	3	2	1 1/2
39	5.75	2	1	2	1	1	1	YES	3	3	2	1 1/2
40	4.63	2	1	2	1	1	1	YES	2 1/2	3	2	1 1/2
43	3.75	1 1/2	2	1	1	1	1	YES	1	3	1	2
49	3.50	1 1/2	2	2	1	1	1	YES	1	3	2	2
61	5.00	2	1	2	1	1	1	YES	2 1/2	3	2	1 1/2
62	3.63	1 1/2	1	2	1	1	1	YES	2 1/2	3	2	1 1/2
66	4.00	2	1 1/2	2	3	1	1	YES	2 1/2	3	3	2
75	4.50	2	1 1/2	2	3	1	1	YES	3	3	3	2
76	3.33	1 1/2	1 1/2	1	3	1	1	YES	2 1/2	3	3	1 1/2
84	3.25	1 1/2	2	1	3	1	1	YES	2 1/2	3	3	2
85	5.50	2	2	2	3	1	1	YES	3	3	3	2
90	3.00	1	2	1	3	1	1	YES	2	3	3	2
91	5.60	2	2	1	3	1	1	YES	3	3	3	2
96	7.25	3	1	2	1	1	1	YES	1	3	2	1 1/2
			23	11	37	29	29		30	35	25	14
			48	61	94	76	88		64	69	76	31

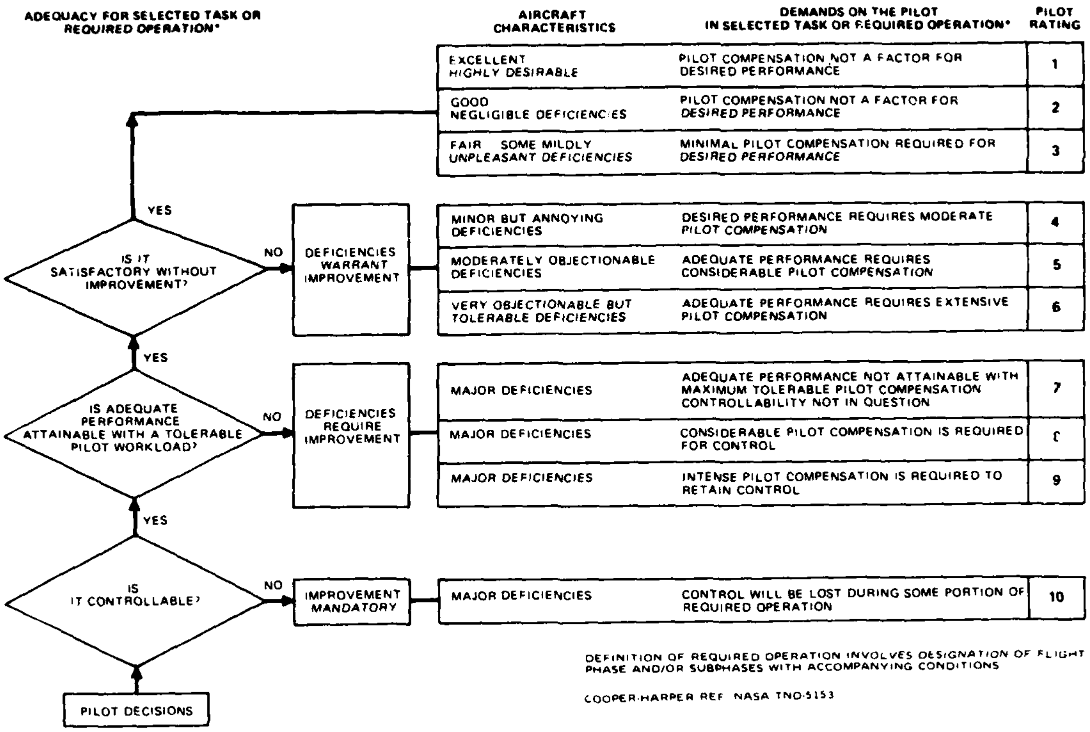


FIGURE 2-4. COOPER-HARPER PILOT RATING SCALE

one pilot, one by two pilots, and the rest by three, four, or five pilots. The average number of ratings per configuration was 3-2/3 for both groups.

While the criteria generally do not have half levels, a configuration that falls near a level boundary probably is indistinguishable from a configuration just across the boundary. Therefore, half levels were created for most of the criteria by the rules given in Table 2-6. Some of the criteria do not have a boundary for every level. The MIL-F-8785B short-period frequency criterion, for example, has a common lower bounday for levels 2 and 3. A level 2 boundary was added midway between the level 1 and level 3 boundaries, as shown in Figure 2-5, *to facilitate evaluation of this criterion.* The ARP 842B short-period criterion is stated, not in terms of levels, but by the terms "acceptable augmented," "acceptable unaugmented," and "unacceptable." These terms bear a similarity to

TABLE 2-6

SOME NOTES ON THE APPLICATION OF THE FLYING QUALITIES CRITERIA

1	PR LEVELS	PR	1 3	3 01 3 99	4 6	6 01 6 99	7 9	9 01 9 49	9 50 10
		LEVEL	1	1 1 2	2	2 1 2	3	3 1 2	4
2	BANDWIDTH MODEL HALF LEVELS WERE CREATED BY SAYING THAT ANY CONFIGURATION WITHIN 0 7 dB OR 3 5° OF A BOUNDARY WOULD BE RATED AS AN AVERAGE OF THE ADJACENT LEVELS								
3	dγ/dV	LEVEL	1	1 1 2	2	2 1 2	3	3 1 2	4
		dγ/dV (deg/kt)	• 0 045	0 0451 0 0749	0 075- 0 135	0 1351 0 1649	0 165 0 225	0 2251 0 2549	0 255 & UP
4	$\omega_{n_{SP}}$ VS n/α SEE FIGURE 2 5 NO HALF LEVELS FOR LOWER BOUNDARIES								
5	*HALF LEVELS FOR OTHER CRITERIA* WHEN PARAMETER FALLS ON OR VERY CLOSE TO BOUNDARY IT IS CONSIDERED HALF WAY BETWEEN LEVELS								
6	R_{10}	THE STANDARD WAY OF APP[illegible]NG MIL F 8785B IS TO COMPUTE FLYING QUALITIES OF AN AIRPLANE FOR A NUMBER OF CRITERIA THE ONLY WAY TO ESTIMATE THE OVERALL FLYING QUALITIES OF THE AIRPLANE IS TO LET IT BE THE SAME AS THE WORST ESTIMATE							
7	R_{13}	THIS CRITERION IS A COMBINATION OF THE DROOP BANDWIDTH CRITERION AND THE dγ/dV CRITERION IF THE LEVEL FOR dγ/dV IS WORSE THAN THE LEVEL FOR BANDWIDTH, THE TWO ARE AVERAGED IF NOT THE BANDWIDTH LEVEL IS TAKEN							

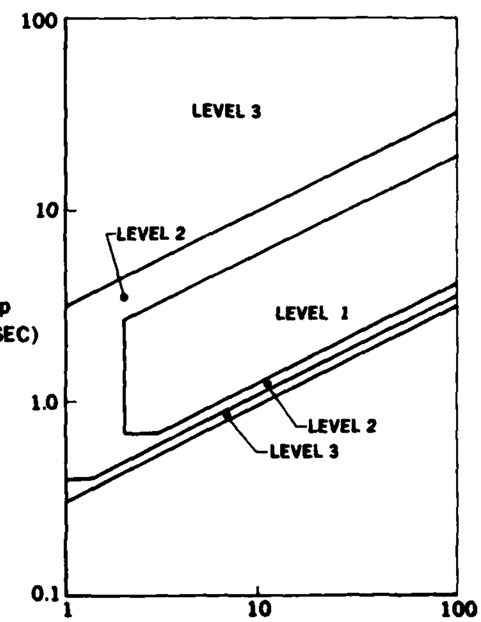


FIGURE 2-5. MIL-F-8785B SHORT-PERIOD FREQUENCY CRITERION

the definitions of the flying qualities levels, so were equated to levels 1, 2, and 3, respectively, as shown on Figure 2-6. Level 1, 2, and 3 regions are similarly defined in Figure 2-7 for the short-period criterion of Reference 2-3.

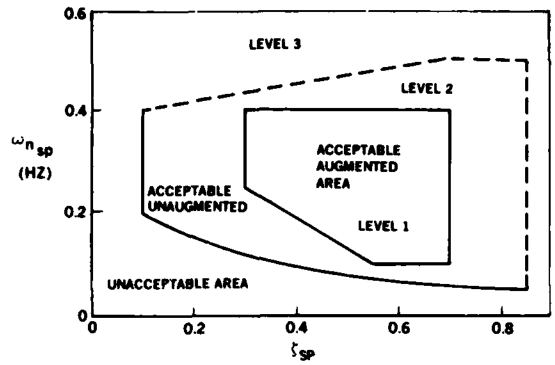


FIGURE 2-6. ARP 842B SHORT-PERIOD CRITERION

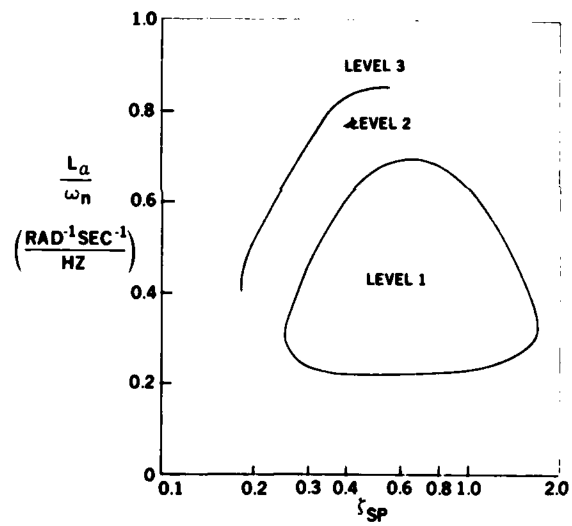


FIGURE 2-7. SHORT-PERIOD CRITERION OF REFERENCE 3

The fourth column, labeled R_1, is the level of flying qualities predicted for each configuration using the Bandwidth Model criterion. The name Bandwidth Model is used to refer to the pilot-model-in-the-loop pitch tracking task criterion. The number at the bottom of the column (23 for Group I and 23 for Group II) is the total error (in half levels) of these predictions. Inspection of the totals for all criteria reveals that the Bandwidth Model criterion is the best performer for the Group I configurations and is second to dγ/dV for Group II.

The flightpath stability criterion (R_2) is the second best performer for the 42 configurations. This is an indication that pilots are more sensitive to bad flightpath response than they are to bad pitch response. The MIL-F-8785B short-period frequency criterion (R_3) was the poorest performer overall and also for Group II, but was slightly better than the worst for Group I. The short-period damping ratio criterion (R_4) performed better than R_3, though pilot opinion should be insensitive to it over a wide range. Even the phugoid stability criterion (R_5) outperformed R_3. The static stability criterion (R_6) was evaluated, but not on the basis of levels. The positive answer was considered an estimate of level 1 to 2-1/2, and a negative answer as level 3 to 4. On this basis, R_6 was wrong for eight of the 26 configurations of Group I. A more meaningful observation is that only half of the statically unstable configurations are level 3 or worse. This means that in half the cases, a requirement for positive static stability was not needed to achieve level 2 flying qualities. The performance of R_6 with Group II is not mentioned because it was not varied in Group II.

There is no methodology in MIL-F-8785B for combining the estimates for several criteria to get an overall airplane level of flying qualities. One can only guess that the overall flying qualities will be as bad as the worst rating, or perhaps worse. Criterion R_{10} is an overall predicted level of flying qualities based on the MIL-F-8785B criteria. It is equal to the worst of R_2 to R_6 and turns out to be a poorer performer than any other criteria except R_3 and R_5. The prediction of R_{10} was better than actual in six cases and worse than actual in 28. While it is better to err on the conservative side, this performance is too conservative.

The last two criteria evaluated, the short-period criteria of ARP 842B (R_8) and of Reference 2-3 (R_9), performed well, being third and fourth best out of eight when both groups are considered. They both performed better than the MIL-F-8785B short-period criteria. Inspection of the data for R_1 and R_2 suggests a combination criterion, R_{13}, which is defined by the equations:

$$R_{13} = R_1 \quad \text{when } R_1 > R_2$$
$$= 1/2(R_1 + R_2) \quad \text{when } R_1 < R_2$$

The results show that this combination criterion is better than any of the other criteria evaluated. The sum of the errors is 31 half-levels for 42 configurations. Further, when the characteristics covered by the various criteria are taken into account, such a criterion makes more sense. The Bandwidth Model criterion is sensitive to all parameters varied in this experiment, except dγ/dV. Thus, a criterion which takes both the Bandwidth Model and dγ/dV criteria into account is sensitive to all the parameters varied in this experiment.

SUMMARY AND CONCLUSIONS

A number of longitudinal flying qualities criteria were evaluated against the results of a motion base simulation of large transport aircraft in the landing approach. The criteria of MIL-F-8785B performed poorly overall. Two short-period criteria, from ARP 842B and Reference 2-3, performed adequately. The best performance was exhibited by a criterion combining the results of a pitch tracking task and the flightpath stability criterion.

REFERENCES

2-1. Anonymous. Flying Qualities of Piloted Airplanes. MIL-F-8785B(ASG), Aeronautical Systems Division, 1969.

2-2. Anonymous. Design Objectives for Flying Qualities of *Civil Transport Aircraft.* ARP 842B, Society of Automotive Engineers, 1970.

2-3. Shomber, H. A., and Gertsen, W. M. Longitudinal Handling Qualities Criteria: An Evaluation. AIAA Paper 65-78, 1965.

2-4. Neal, T. P., and Smith, R. E. An In-Flight Investigation to Develop Control System Design Criteria for Fighter Airplanes. AFFDL-TR-70-74, Volumes I and II, 1970.

2-5. Wasserman, R., Mitchell, J. F., Rickard, W. W., Huber, R. W., and Schelhorn, A. E. In-Flight Investigation of Minimum Longitudinal Stability for Large Delta-Wing Transports in Landing Approach and Touchdown. AFFDL-TR-72-143, Volume II, 1973.

A Model-Based Technique for Predicting Pilot Opinion Ratings for Large Commercial Transports*

by

William H. Levison
Bolt Beranek and Newman Inc.
Cambridge, Massachusetts

Presented at the Symposium/Workshop on Flying Qualities
Design Criteria
Wright-Patterson AFB, Ohio
October 9 and 10, 1979

ABSTRACT

A model-based technique for predicting pilot opinion ratings is described. Features of this procedure, which is based on the optimal-control model for pilot/vehicle systems, include (1) capability to treat "unconventional" aircraft dynamics, (2) a relatively free-form pilot model, (3) a simple scalar metric for attentional workload, and (4) a straightforward manner of proceeding from descriptions of the flight task environment and requirements to a prediction of pilot opinion rating. The method was able to provide a good match to a set of pilot opinion ratings obtained in a manned simulation study of large commercial aircraft in landing approach.

INTRODUCTION

Manufacturers of commercial aircraft require more general and more reliable methods of predicting aircraft handling qualities than currently exist. Existing criteria have been developed primarily for military aircraft and have been validated largely for high-performance aircraft such as fighters. At present, reliable techniques for extending existing criteria to large commercial transports are not available.

* The research described in this paper was supported by NASA Langley Research Center under Contract No. NAS1-15529.

This paper summarizes the results of a study performed by Bolt Beranek and Newman Inc. (BBN), with the aid of Douglas Aircraft Company (Douglas), to develop and test a model-based technique for predicting the influence of aircraft response parameters and other relevant factors on pilot opinion ratings. While the procedure is intended to have general application, the focus in this paper is on large transports. Frequent reference is made to a manned simulation study performed by Douglas in 1975.* To facilitate discussion, the analytic study that is the subject of this paper will be referred to as the "BBN study", whereas the preceding simulation program will be referred to as the "Douglas study". Further documentation of the BBN study is provided in [1].

Vehicle-Centered Handling Qualities Criteria

Handling qualities specifications are based almost exclusively on open-loop vehicle response characteristics [2]. Criteria are specified for both transient response and frequency response characteristics.

Handling qualities requirements based on vehicle response characteristics -- particularly frequency-response behavior -- are convenient because the aircraft manufacturer can evaluate the performance of his aircraft in this regard through a series of relatively straightforward in-flight tests. He need not be concerned with the interaction between the vehicle and the pilot, which, of course, will vary from one test pilot to the next. The ease with which compliance can be tested, plus the existence of a substantial body of relevant handling qualities data, provide a strong motivation to relate handling qualities to open-loop vehicle response characteristics.

Despite the relative convenience with regard to compliance testing, application of vehicle-centered handling qualities specifications to large commercial transports is limited in a number of ways; for example:

a. Existing handling qualities criteria have been developed primarily for military aircraft. Furthermore, these criteria have been validated largely for high-performance aircraft (fighters, etc.) Thus, application to large commercial transports cannot be undertaken with great confidence.

---

* This effort included a subcontract to Douglas Company to provide a data base extracted from the 1975 Douglas simulation study and to provide other consulting services. Mr. William W. Rickard was project engineer for the Douglas effort.

b. Most existing criteria are based on simple models of aircraft dynamics in which phugoid and short-period response characteristics can be distinguished. Consequently, application to aircraft having relaxed static stability and substantial control augmentation is dubious at best.

c. For the most part, effects of turbulence are not considered. This oversight neglects a potentially important aspect of flying qualities and is a consequence of considering only open-loop aircraft characteristics.

d. Effects of displays (such as flight directors) are not considered. To the extent that display parameters influence overall mission suitability (and, therefore, pilot opinion rating), a method for predicting handling qualities should account for the effects of display parameters.

e. Present method do not consider effects of dynamic aeroelasticity.

Model-Based Schemes for Predicting Handling Qualities

Pilot/vehicle analysis can allow considerably greater insight into the handling qualities of an aircraft control system than can be obtained by analysis of open-loop response (which is usually what counts in terms of meeting mission requirements), and the demands made on the pilot can be explored. The effects of external disturbances and control/display parameters, as well as inherent pilot limitations, can be considered. Furthermore, predictive schemes based on pilot/vehicle analysis are not constrained to deal with "conventional" dynamics and are thus potentially more general than techniques based solely on open-loop vehicle characteristics.

Until recently, application of pilot/vehicle analysis to studies of vehicle handling qualities has been based primarily on servo-theory techniques. Central to these techniques is a frequency-domain model of the pilot which is generally structured so that feedback loops are closed serially, rather than in parallel. Typically, the pilot's control strategy for each loop is represented by a low-frequency gain, a lead-lag network, and an equivalent time delay to represent inherent information-processing delays. (Usually, pilot neuromuscular lags are neglected or are incorporated into the effective time delay.)

Analysis of the pilot/vehicle system is based on the assumption that the pilot attempts to achieve "good" performance in terms of the gain-crossover frequency and phase margin associated with each control loop. Ideally, crossover frequencies are kept sufficiently large to assure adequate response bandwidth while comfortably large phase margins and damping ratios are maintained in order to assure high-frequency stability. By use of root locus techniques, a set of pilot gains and lead time constants is found which best satisfies these requirements. If the closed-loop frequency response is not within the desired envelope, or if substantial pilot lead generation is required, then the pilot rating has to be degraded to take these factors into account [3].

Perhaps the most comprehensive effort to apply classical control theory to the prediction of aircraft handling qualities has been conducted by R. O. Anderson and his associates in the development of the "Paper Pilot" analysis scheme [4]. This scheme relates pilot rating to metrics of both closed-loop system performance and pilot workload, and it introduces the concept that the pilot operates so as to minimize his rating score.

Pilot rating is assumed to be an explicit function of system performance and pilot lead requirements (lead compensation being the index of pilot workload in this scheme). A pilot model of the type described above is used in this scheme, and pilot parameters are adjusted to minimize pilot rating. Good matches to experimental data have been obtained for a variety of control tasks through appropriate formulation of the rating expression and adjustment of the relative weighting coefficients associated with performance and workload (i.e., pilot lead) [4-7].

This analysis scheme allows one to account for some of the factors (other than open-loop vehicle response characteristics) that influence pilot opinion. Pilot compensation and gain requirements are determined directly, and the susceptibility of the system to PIO's can be estimated from the closed-loop pole-zero and Bode plots. Effects of external disturbances, and to some extent display parameters, are accounted for.

Perhaps the most serious limitation of the Paper Pilot scheme is that no general rule has yet been determined for choosing the precise form of the rating expression or for selecting the various weighting coefficients. Other factors limiting the generality of this and other procedures based on servo-theory models include:

(a) use of a relatively constrained fixed-form pilot model;
(b) the need to assume specific loop closures prior to analysis;
(c) a cumbersome treatment of pilot workload, especially when multiple loops are closed; and (d) the inability to account directly for factors related to the perceptual environment (e.g., perceptual resolution limitations, whole-body motion cues).

Building on the ideas of Anderson, staff members of Bolt Beranek and Newman (BBN) Inc., suggested a model-based scheme to overcome some of these limitations.* Attentional workload was defined in terms of a model parameters, and the pilot was assumed to tradeoff between workload and a scalar metric of system performance to minimize the numerical pilot rating. A rating expression, formulated as a function of "workload" and performance, was tested against existing experimental data with encouraging results.

More recently, Hess [8] has described a model-based scheme for predicting pilot raitngs similar to that suggested by BBN. He suggests an index of performance that consists of a weighted sum of integral- (or mean-) squared error and control terms. "Error" is a vector quantity that consists of the system variables that the pilot wishes to maintain within acceptable limits. The pilot is assumed to adopt control and estimation strategies that minimize this performance index.

Hess proposes a model structure, based on modern (or "optimal") control theory, to allow one to predict the performance index for various flight tasks. This model is a modified implementation of the model originally suggested by Kleinman, Baron, and Levison [9, 10]. The latter model forms the basis for the prediction scheme that is the subject of this paper.

Hess tested his scheme against 19 different configurations covering a range of pilot ratings. "Cost" coefficients of the quadratic performance index were chosen to match experimental scores, and pilot-related model parameters were chosen partly on the basis of previous results and partly to match observed performance. Pilot ratings could be matched to within ± 1 rating unit by a linear relationship between pilot rating and the logarithm of the performance index. More recently, Schmidt has used this prediction scheme as the basis for a model-based control design procedure [11].

---

* "A Technique for Predicting Aircraft Handling Qualities as a function of System Performance and Attentional Demand", Technical Memorandum CSD-7, November 1974, Control Systems Department, Bolt Beranek and Newman Inc., Cambridge, Massachusetts.

Although not validated as a reliable predictive tool, Hess' procedure lays the foundation for a scheme that seems to overcome some of the limitations inherent in techniques based on classical servo analysis. The basic form of the performance index is consistent across tasks, the form of the pilot model and nature of loop closures are determined by the optimal pilot model and need not be specified by the user, a scalar metric of workload is provided, and factors related to perceptual environment are considered.

Perhaps the most severe limitation of the optimal-model-based approach, as developed so far, is the requirement to specify numerous task- and pilot-related model parameters. To some extent, the "artistry" in specifying pilot model forms and loop closures for servo-theory models is replaced by the artistry in specifying parameters (especially weighting matrices) of the optimal-control model.

Another limitation, in the opinion of this author, is the lack of a suitable metric for information-processing workload. The metric proposed by Hess (the number of system variables to be regulated) does not appear to add to the rating scheme beyond what is encompassed by the *performance* index. That is, if workload is to be related to controlled variables that are of concern to the pilot, then only those variables contributing significantly to the performance index will increase pilot workload. Such effects are accounted for by the numeric value of the index itself.

The methodology described in this paper builds upon the work of Hess and encompasses a pilot rating prediction scheme based on the optimal-control model for pilot/vehicle performance. Emphasis is placed on the predictive aspects of the procedure, and a rationale is offered for selecting model parameters on the basis of an adequate description of the task and in the absence of experimental data. In addition, a well-defined model parameter is suggested as a potential scalar workload metric for the purposes of predicting pilot opinion ratings.

METHODOLOGY

Because pilot opinion is assumed to reflect both pilot workload requirements as well as system performance capabilities, methods for predicting pilot ratings should include consistent and straightforward treatments of workload. Therefore, before proceeding with a description of the proposed rating scheme, let us briefly review the concept of workload as used in this study.

The term "workload" is intended to refer to information-processing -- rather than physical -- activity of the pilot. Specifically, workload is considered synonomous with "attention" in the remainder of this paper. Although attention is not defined here in a way that lends itself to direct physical measurement, the pilot model used in the rating prediction scheme does include a parameter that can be related to attention on both theoretical and empirical grounds. Thus, for the purposes of obtaining rating predictions, attention (workload) is an unambiguous and workable concept.

Basic Approach

The prediction scheme described in this report is based on the following assumptions: (a) pilot rating is a function of the flight task; (b) for a given flight task there exist one or more critical subtasks which serve as the primary determinants of pilot rating; (c) performance requirements are well defined for each critical subtask; (d) pilot opinion is based partly on the degree to which desired performance is achieved and partly on the information-processing workload associated with the task; and (e) a reliable model exists for predicting performance/workload tradeoffs for relevant flight tasks.

These assumptions lead to the procedure diagrammed in Figure 1. The following steps are required for predicting an average pilot rating for a specific situation.

1. Task Definition. Pilot opinion ratings are task dependent. For example, the rating associated with a specific vehicle, relative to other vehicles or other configurations of the same basic airframe, may not be the same in final approach as, say, in high-altitude cruise. Therefore, separate assessments must be made for each flight task of interest.

2. Subtask Definition. Use of the methodology requires a quantitative description of the specific task or subtask for which predictions are to be obtained. For example, if ratings are desired for landing approach, a critical aspect of that task (say, ILS tracking) must be quantified. Task specification requires a linearized description of vehicle dynamics plus a quantitative description of the external environment (e.g., spectral characteristics of the wind gusts if the subtask is path regulation in the presence of zero-mean random turbulence).

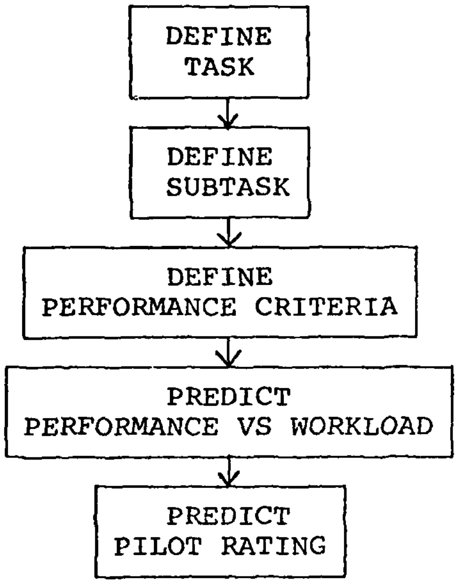


Figure 1. Procedure for Predicting Pilot Rating

3. Define Performance Criteria. Performance criteria must be defined in precise quantitative terms. In order to obtain performance/workload predictions with the pilot/vehicle model used in this procedure, a quadratic performance index containing error- and control-related terms must be specified. The user must specify both the terms to be included in the performance index as well as values for the cost weighting coefficients. Cost weighting coefficients based on assumed maximum allowable values are suggeted. As illustrated below, these coefficients are determined partly from the physical constraints of the flight control system, partly from objective performance requirements of the closed-loop system, and partly from pilot preference. The performance criterion used in the rating expression should be a monotonic functin of this quadratic performance index.

4. Predict Performance/Workload Tradeoff. The "optimal-control" pilot/vehicle model is used to predict performance as a function of information-processing workload. "Workload" -- considered synonymous with "attention" in the context of the model -- is defined in terms of a model parameter relating to signal/noise characteristics of the human operator.

5. Predict Pilot Rating. The results of the preceding step are used in a rating expression to predict the pilot rating. If experimental data are available for the flight task/subtask of interest, a regression analysis is performed to "calibrate" the independent parameters of the rating expression; in this case, absolute rating predictions are obtained. In the absence of such calibration data, rating parameters are adjusted on the basis of previous results, and rating predictions are interpreted on a relative basis with regard to predictions obtained for other vehicle configurations.

2.2 Pilot/Vehicle Model

The prediction technique described in this paper is built around the so-called "optimal-control" model for pilot/vehicle systems. The theoretical foundation for this model has been described in the literature [9, 10], and the model has been validated for both simple laboratory tracking tasks [9, 10, 12-14] as well as for more complex control situations [15-17]. As discussed above, this model has also been shown to yield good handling qualities predictions [8].

Key features of the model are summarized below. The reader is directed to the literature for details on theoretical development and validation.

The model is based on the assumption that the well-motivated, well-trained human operator behaves in a near optimal manner subject to his inherent constraints and limitations. The operator is assumed to adopt strategies of state estimation and control that minimize a "cost function" (or performance index) of the form:

$$J = E \{\lim_{T \to \infty} \frac{1}{T} \int_0^T [\sum_{i=1}^{N_y} q_i y_i^2 (t) + \sum_{i=1}^{N_u} (r_i u_i^2 (t) + g_i \dot{u}_i^2 (t)] dt\} \quad (1)$$

where the y_i are system variables (observed by the pilot) that are to be maintained within acceptable limits, u_i are the pilot's control inputs, and q_i, r_i, and g_i are weighting ("cost") coefficients.

Pilot-related limitations reflected in the model include information-processing delay, response bandwidth limitations, response randomness, and limitations related to perception.

Information-processing delay is accounted for by a pure time delay which, for mathematical convenience, is associated with the perceptual process. Generally, a time delay of 0.2 $\pm$ 0.05 seconds provides a good match to experimental data. To the extent that control activity is limited by operator response limitations (as opposed to limitations of the physical control system), a good match to experimental data can be obtained by selecting the cost coefficient on control rate to yield a lag time constant of approximately 0.1 seconds. (This lag is not lumped into the pure delay term.)

The "observation noise" and "motor noise" parameters account for response randomness; the former accounts as well for perceptual limitations. The motor noise term is included primarily to reflect limitations in the pilot's knowledge of the response characteristics of his vehicle; a typical value of motor noise is -60 dB, normalized with respect to control-rate variance.*

The stochastic portion of the pilot's response ("pilot remnant") is accounted for largely by an observation noise process. Each perceptual variable utilized by the pilot is assumed to be perturbed by a Gaussian white noise process linearly independent

---

* Various representations of motor noise have been explored during the development of the optimal-control model [18, 19]. For the version used in this study, motor noise was represented as a Gaussian white noise process injected in parallel with commanded control rate and normalized with respect to the varaince of the commanded control rate.

of other such noise processes and of external inputs to the system. In the case of a single-variable steady-state tracking task in which perceptual threshold- and saturation-type limitations are negligible, the variance of each observation noise process appears to scale with the variance of the associated perceptual variable. Thus,

$$V_i = \pi P_i \, \sigma^2_{y_i} \qquad (2)$$

where $y_i(t)$ is the i^{th} perceptual variable, $\sigma^2_{y_i}$ is the variance of that variable, p_i is the "observation noise/signal ratio" associated with perception of y_i, and v_i is the autocovariance of the white observaton noise processes. This expression can be modified to account for limitations associated with perceptual resolution [20].

The model is able to reproduce pilot response behavior in a number of simple laboratory tracking tasks with a nearly constant value of noise/signal ratio of about 0.01 (i.e., -20 dB). The consistency of this parameter across tasks and across subject populations suggests that it reflects a basic central-processing (rather than perceptual or motor) limitation, and these results have led to the following model for central attention sharing:

$$P_i = \frac{P_o}{f_i} \cdot \frac{1}{f_t} \qquad (3)$$

where f_t is the fraction of attention devoted to the tracking task as a whole, f_i is the subfraction of such attention devoted to display variable y_i, and P_o is the baseline noise/signal ratio associated with a high-workload single-variable tracking task (typically, -20 dB).

The attention-sharing model of Eq. (3) has a theoretical base [21] and has been validated in a study of multi-axis tracking by Levison, Elkind, and Ward [12], who found that this model yielded accurate predictions of multi-axis system performance. Wewerinke [22] has also obtained generally good agreement between subjective workload assessments and a "workload index" based partly on this model. (Wewerinke's workload index uses both the noise/signal ratio at which the pilot operates, as in the model suggested here, plus the sensitivity of the performance index to fractional changes in this noise ratio.)

When analyzing tasks using symbolic displays, it is usually assumed that attention must be shared among the display elements used by the pilot; that is, information obtained from one element at the cost of degrading the information obtained from another.* If the large eye movements are necessary, visually obtained information is further degraded because of the apparent loss of perception that occurs immediately before, during and after each eye movement [23]. This loss is modeled by letting the f_i sum to a value less than unity. Thus,

$$\sum_i f_i = 1 - f_o \qquad (4)$$

where f_o is the fraction of time "lost", on the average, because of scanning. If displays are centrally located and attention-sharing is primarily central in origin, f_o is assumed zero and fractional attentions sum to unity.

In a specific application, values for f_i may be chosen (subject to the above constraint) to reflect some hypothesized allocation of attention, or model solutions may be used to find the allocation of attention that yields optimum performance. That is, one may use the model to predict the optimal allocation of attention.

The model parameter, f_t, representing attention to the control task as a whole, serves as the metric for workload in the proposed handling qualities prediction scheme. Because it is a scalar quantity, it may be used in a straightforward manner to predict handling qualities for multi-variable, multi-axis flight control tasks. Unlike workload metrics used in alternative model-based prediction schemes, the attention parameter defined here has a theoretical as well as empirical basis.

---

* No interference is assumed between position and rate information obtained from the display element.

Because the predicted "cost" for a given task increases monotonically with increasing noise/signal ratio, and because noise/signal ratio is related inversely to the attention parameter f_t, cost is a monotonically decreasing function of "workload" as we have defined it here. Thus, if other independent model parameters are kept fixed, tradeoff curves of performance versus workload can be predicted for configuration of interest. As described below, these curves can be further processed to yield predictions of pilot rating.

Prediction of Pilot Rating

In keeping with Anderson's philosophy [4], pilot rating is predicted by means of a mathematical expression that includes both performance and workload effects. In general, "performance" is defined in terms of the performance index of Eq. (1) or some other scalar function of the signal deviations predicted by model analysis. As described above, "workload" is synonymous with the total attention to the task, f_t, which affects performance through the noise/signal ratio.

Best results in this study were obtained through use of a performance metric defined as the joint probability of one or more system variables being outside their respective "limits" (i.e., maximum desirable values). The following alternative philosophies were tested and found to yield good replications of experimentally obtained pilot ratings: (1) pilot rating is determined by the performance achievable at some particular level of workload; (2) pilot rating is determined by the workload required to achieve some criterion level of performance; and (3) pilot rating is a continuous function of both performance and workload, and the pilot operates at a workload so as to minimize the numeric value of his rating (i.e., achieve the best rating).

These philosophies were implemented, respectively, by the following rating expressions:

$$R = 1 + 9 \left. \frac{\sigma}{\sigma + \sigma_o} \right|_{A=A_o} \tag{5}$$

$$R = 1 + \left. \frac{1}{A + A_o} \right|_{\sigma=\sigma_o} \tag{6}$$

$$R = 10 \left[\frac{\sigma}{\sigma + \sigma_o} + \frac{A}{A + A_o} \right] \tag{7}$$

$$1 < R < 10$$

where R is the predicted pilot rating on the Cooper-Harper Scale [24]; σ is predicted performance in terms of a probability as defined above, A is the attention model apràmeter (equivalent to f_T of Eq. (3)), and σ_o and A_o are constants of the rating expressions.* For convenience, we shall refer to these rating expressions as the "performance model", the "attention model", and the "minimum-rating model".

The first two expressions are intended as predictors of rating only, not as predictors of the specific point on the performance-workload tradeoff curve at which the pilot will operate. The minimum-rating expression of Eq. (7), on the other hand, embodies the notion expressed by Anderson that the pilot trades between performance and workload in such a way as to minimize the rating score. In principle, use of the minimum-rating expression should allow one to predict pilot workload and overall system performance as well as the pilot rating.

DATA BASE

The data base used for developing and testing the handling qualities prediction scheme was obtained from two sources: (1) an experimental study performed by Douglas Aircraft Company in 1975, [25], and (2) the results of a questionnaire, submitted during the course of this study, to the test pilots who participated in the Douglas study.

Description of Experiments

A manned simulation study was conducted by Douglas to explore the applicability of various handling qualities criteria to longitudinal flying qualities of large transport aircraft in the landing approach. Criteria that were evaluated included several vehicle-centered criteria from MIL-F-8785B [1], vehicle-centered criteria from other sources [25], and a pitch tracking criterion involving a closed-loop pilot model [2]. This study is described in detail by Rickard [25]; a summary of the experiments is given below.

---

* Numerical values for A_o and σ_c may vary from one expression to the next.

The Douglas study explored a total of 42 vehicle configurations. The first group of 26 configurations were obtained by selecting stability derivatives typical of wide-body aircraft and either varying the simulated cg location from far forward to far aft of the neutral point, or by varying a single stability derivative. Configurations of the second group were obtained by specifying vehicle frequency-response characteristics and then solving for the stability derivatives. All handling-qualities variations were confined to the longitudinal control axis; lateral-directional aircraft parameters were kept fixed throughout the experiment to provide response characteristics typical of a wide body transport.

Five Douglas test pilots performed evaluations of these configurations on a six-degree-of-freedom moving-base simulator. Each evaluation typically consisted of two ILS approaches: the first performed in the absence of simulated atmospheric disturbances, the second in the presence of simulated zero-mean turbulence. Approach was initiated at a range of 7.4 n. mi. from runway threshold at an altitude of 1500 feet on the extended runway centerline. The 3-degree glide slope was intercepted at a range of about 4.7 n. mi.; the pilot flew down the glide slope relying on ILS instrumentation for path information to an altitude of about 700 feet, at which point the pilot transitioned to a visual display for flare and touchdown.

The test pilots were encouraged, in general, to perform maneuvers that would aid in their evaluations (e.g., intentionally impose and then eliminate a path or attitude error), but no specific set of maneuvers was required. A single Cooper-Harper rating was given by each pilot for the pair of still-air and turbulent-air approaches for each configuration. Some configurations were evaluated more than once by some of the test pilots. Evaluations were performed on the basis of approach performance only; flare and touchdown characteristics were not considered.

Configurations Explored in the BBN Study

The rating expressions described in Eq. (5) - (7) were tested against eight configurations selected from the first group used in the Douglas study. These configurations were chosen to span a range of pilot ratings as well as a range of handling qualities problems. Modal characteristics for the configurations explored in the BBN study are given in Table 1.

TABLE 1

Configuration Characteristics

$v = 140$ kts $\gamma = -3^{o}$ wt = 350,000 lbs

Config.* Number	ω_{sp}	ξ_{sp}	ω_{ph}	ξ_{ph}	n/α	$d\gamma/dV$	$1/T_{\theta 1}$ or $[\omega]$	$1/T_{\theta 2}$ or $[\xi]$
1	0.846	0.628	0.186	0.072	3.80	-0.040	-0.084	-0.506
3	(-0.633)	(-0.307)	0.086	0.318	4.14	-0.049	-0.082	-0.556
4	(-0.811)	(+0.090)	0.200	0.636	4.20	-0.051	-0.082	-0.564
5	(-0.909)	(+0.158)	0.210	0.479	4.24	-0.053	-0.082	-0.568
8	0.811	0.662	0.194	0.041	4.04	+0.339	+0.041	-0.631
15	(-0.991)	(+0.225)	0.211	0.388	4.29	-0.055	-0.082	-0.575
16	(-1.061)	(+0.291)	0.210	0.331	4.35	-0.057	-0.082	-0.583
21	0.441	0.665	0.170	0.043	1.05	+0.285	[0.149]	[0.676]

ω_{sp} = short-period natural frequency, rad/sec

ζ_{sp} = short-period damping ratio

ω_{ph} = phugoid natural frequency, rad/sec

ζ_{ph} = phugoid damping ratio

n/α = normal acceleration per unit angle of attack, g/rad

$d\gamma/dV$ = path angle change per speed change, deg/kt

T_θ = numerator time constant, sec

(   ) signifies first-order factor

* Configuration number of the Douglas Study [25].

The test pilots were assumed to utilize the ILS instrument, attitude indicator, and airspeed indicator as their primary displays during the instrument-flight portion of the simulated approach.

Zero-mean turbulence was simulated in the three linear and three rotational degrees of freedom in the Douglas study. Turbulence models(based on models suggested in the flying qualities specifications [1]) were used to provide disturbances to longitudinal-axis variables. RMS u- and w- gust levels were fixed at 7.8 ft/sec and 6.5 ft/sec, respectively. Further details on these gust models are given in reference [1].

Performance Requirements

Application of the prediction scheme described above requires that one or more specific subtasks be selected for analysis and that performance requirements be specified for each subtask. To obtain this information, a questionnaire was prepared by BBN and administered by Douglas personnel to 4 of the 5 test pilots that had participated in the 1975 manned simulation study. Through this questionnaire the pilots were requested to (1) state whether or not pilot ratings were determined primarily by longitudinal handling characteristics; (2) specify whether ratings were based mainly on the instrument-flight or visual-flight portions of the approach; (3) specify, in order of priority, the subtasks that were important determinants of pilot rating; and (4) specify in as quantitative manner as possible the "desired" and "acceptable" levels of performance for each subtask. A sample of the questionnaire is provided in reference [1].

All four pilots agreed that lateral-directional handling qualities were quite satisfactory and that pilot ratings were influenced primarily by longitudinal handling characteristics. They all stated that the instrument-flight phase was more important in determining ratings.

All subjects indicated at least three subtasks as important determinants of pilot rating. Relative importance of these subtasks for the subject population as a whole was determined from "priority score", computed by assinging 5 "points" to an item receiving highest priority, 4 points to the next priority, and so on to 1 point for tasks ranked fifth or more in the list. Priority scores for each task are shown in Table 2, along with the total score obtained by summing across pilots.

Table 2

Priority Scores for Important Subtasks

Subtask	LB	BM	JM	AT	Total
	Priority Score				
Glide-Slope Capture	5	5	4	4	18
Glide-Slope Tracking	4	-	2	5	11
Recover from Glide Slope Mistrim	3	3	1	4	11
Altitude Station-Keeping	-	4	5	-	9
Open-loop Response	-	2	3	3	8
Recover from Airspeed Mistrim	2	-	1	-	3
Recover from Pitch Mistrim	-	-	1	-	1

Table 2 shows that ratings were largely determined by the ability of the pilot to regulate path error. Highest pricty was given to tasks involving transient maneuvering (glide-slope capture, correcting self-induced height error). Next in importance were tasks requiring continuous regulation of height error (altitude station-keeping prior to glide slope acquisition, post-acquisition glide-slope tracking). Open-loop response and correction of pitch and airspeed mistrim were of substantially less importance overall in terms of influencing pilot opinion.

Obtaining quantitative comments related to performance requirements was considerably more difficult than anticipated. Only two of the four pilots provided quantitative responses, and only one of these (Subject JM) differentiated between "desired" and "acceptable" performance.* Performance requirements indicated by these two subjects for tasks requiring continuous regulation are given in Table 3.

Table 3

Subjective Performance Requirements

	JM				BM
	Alt. Regulation		G-S Tracking		G-S Tracking
	Desired	Acceptable	Desired	Acceptable	
Height Error	± 30 ft.	± 100 ft.	± 1/4 dot	± 1/4 dot at 200' ± 1 dot at 1100'	± 1/4 dot
Sinkrate Error (ft/min)	± 200	± 500	± 200	± 500	-
Airspeed Error (knots)	± 5	± 10	± 2	± 5	- 5, + 10

* To aid the pilot in making this distinction, "adequate" performance was defined in the questionnaire as corresponding to the boundary between a rating of 6 and 7, whereas "desired" performance was to be associated with a rating of 1.

Pilot Ratings

Mean and standard deviations of the pilot ratings obtained in the Douglas study are given in Table 4, along with handling qualities levels as determined from two of the vehicle-centered criteria considered by Rickard [25]. Rating statistics were derived by first averaging multiple ratings (where such existed) for each pilot for each configuration, and then using these averages to compute a mean and standard deviation across subjects for each configuration.*

Table 4

Pilot Opinion Ratings

Config.	Pilot Rating Mean	Pilot Rating SD	$d\gamma/dV$ Level	ω_{sp} vs. n/α Level	Static Stability
1	2.5	1.5	1	1	Yes
3	4.3	2.3	1	4	Yes
4	4.2	2.1	1	4	No
5	5.3	1.6	1	4	No
8	8.3	2.1	4	1	Yes
15	6.7	1.5	1	4	No
16	7.7	2.5	1	4	No
21	6.2	3.5	4	2	Yes

Mean rating for 5 pilots, configurations 1,2,4,5

Mean rating for 3 pilots, configurations 8,15,16,21

Table 4 shows both a wide spread of average pilot ratings across the configurations explored in the BBN study as well as a variety of handling qualities problems. The short-period response criterion predicts adverse handling qualities for five of the configurations -- four of which exhibit static instability. Two of the remaining configurations, on the other hand, exhibit adverse flight path stability ($d\gamma/dV$).

TEST OF METHODOLOGY

The prediction scheme described above and diagrammed in Figure 1 was applied to the data base obtained in the 1975 Douglas study. In order to apply this scheme, twenty independent model parameters had to be specified. As the following discussion demonstrates, eighteen of these parameters were defined largely on the basis of task analysis, tempered by some engineering judgement.

---

* Ratings shown for configurations 4 and 5 differ slightly from those presented by Rickard, who computed the mean of all ratings pertaining to a given configuration regardless of the number of evaluations per pilot.

Once selected, these parameter values were held fixed throughout the analysis; only the two parameters of the rating expression were adjusted to match experimental data.

Problem Definition

The methodology described in this paper was applied to the general flight task of final approach, exclusive of landing. On the basis of the questionnaire submitted to the Douglas test pilots, two specific subtasks were initially selected for study: continuous glide-slope tracking in turbulence, and recovery from intentional glide-slope offset. Preliminary exploration of the latter (transient) task was performed, but resources permitted a complete analysis of only the continuous tracking task. Therefore, discussion is confined to tests based on the continuous tracking task.

Although continuous in nature, glide-slope tracking following capture is not, strictly speaking, a steady-state task because of time variations in various task parameters. For example, (a) turbulence bandwidth changes with altitude; (b) path control becomes more important as the touchdown point is approached; and (c) since the ILS instrument displays path error in terms of angular deviation, the effective display gain (inches of indicator deflection per foot of height error) also varies with range. Nevertheless, because these time variations are slow compared to the time constants of important system variables, piecewise-steady-state analysis can yield meaningful predictions of pilot/vehicle performance at various points along the glide path.

A "frozen-point" analysis was performed at a simulated altitude of 1000 feet. Parameters of the turbulence model appropriate to this altitude (see reference [1]) were chosen for this analysis.

Weighting coefficients for the quadratic performance index given in Eq. (1) were selected as the reciprocals of the maximum allowable deviations (or "limits") on important system variables -- a procedure that has been followed with apparent success in previous applicatins of the optimal-control pilot model [8, 17, 27]. Limits of 117 ft. height error (corresponding to 1 dot glide-slope deviation at an altitude of 1000 ft.) and 10 kts (16.9 ft/sec) airspeed error were chosen on the basis of pilot commentary summarized in Table 3. Limits of 40 pounds stick force (10 degrees elevator deflection), 60 pounds/sec force rate, and 21,500 pounds thrust were chosen, in part, on the basis of physical constraints of the control system. A limit of 10,750 pounds/sec rate of change of thrust was chosen to induce a control-related lag time constant of about 2 sec; this selection was based on the assumption that the pilot would not make continuous wide-band throttle movements during approach.

No limits (i.e., no terms in the quadratic performance index) were associated with either sinkrate error or attitude variables. Penalties on attitude variables were omitted because no limitations on such variables were specified by the test pilot; sinkrate error was omitted from the performance index to prevent overemphasis on height-related variables. Despite the lack of explicit performance penalties on attitude variables, the penalties on control-related variables constrained the model to predict a reasonable "mix" of height, attitude, and control deviations.

The pilots were assumed to make longitudinal-axis flight-control inputs primarily on the basis of perceptual information obtained from the ILS, attitude, and airspeed instruments. Rate information was also assumed to be obtained from the ILS and attitude indicators. Thus, the "display vector" assumed for model analysis consisted of height, sinkrate, pitch, pitch rate, and airspeed errors.

Attention was assumed to be divided equally between the ILS attitude, and airspeed instruments;* no attention-sharing penalties were considered between displacement and rate information from the same physical display. On the basis of analysis performed in a previous analytic study of landing approach [17], 34% of the pilot's attention was assumed to be "lost" because of large eye movements required to scan the flight-control instruments. Thus, fractional attentions of 0.22 were associated with the ILS, attitude, and airspeed displays.

Effective perceptual thresholds were computed from the display gains (i.e., inches of display deflection per unit change in problem variable), the eye-to-display distance, and assumed values of perceptual resolution limitations based on previous laboratory experiments as described by Levison [1]. A residual noise was also associated with perception of pitch attitude change. Display and performance-related model parameters are given in Table 5.

---

* To be entirely consistent with the notion of optimal pilot response behavior, an allocation of attention should be determined that minimizes the performance index. Previous studies have shown, however, that an equal allocation of attention among essential display variables yields model predictions very close to those obtained with optimal attention sharing [27]. Therefore, to simplify the analysis, uniform attention-sharing was assumed.

Table 5

Display- and Performance-Related Model Parameters

Variable	Limit	Cost Coefficient	Threshold	Residual Noise	Relative Attention
h	117	7.31 E-05	9.3	0	.22
$\dot{h}$	-	-	37.	0	.22
θ	-	-	.43	0.5	.22
q	-	-	1.72	0	.22
u_i	16.9	3.5 E-03	1.9	0	.22
δ_e	40	6.25 E-04	-	-	-
$\dot{\delta}_e$	60	2.78 E-04	-	-	-
δ_t	21,500	2.16 E-09	-	-	-
$\dot{\delta}_t$	10,750	8.65 E-09	-	-	-

h = altitude error, feet

θ = pitch change, degrees

q = pitch rate, degrees/second

u_i = airspeed relative to moving air mass, feet/second

δ_e = force on the control column, pounds

δ_t = thrust deviation from trim, pounds

Additional pilot-related model parameters -- not shown in the table -- were (a) an observation noise/signal ratio of -20 dB associated with a relative attention of unity, (b) a motor noise/signal ratio of -60 dB, and (c) a time delay of 0.2 seconds.

Prediction of Performance/Workload Tradeoffs

Performance/workload tradeoffs were predicted for each of the eight configurations defined in Table 1. For purposes of predicting handling qualities, "performance" was defined as the probability of one or more system variables exceeding maximum allowable values. To obtain an approximation to this joint probability, system variables were treated as independent Gaussian variables,

$$Pr = 1 - \sum_i (1-Pr_i) \tag{8}$$

where Pr_i is the probability that the i^{th} variables of interest will lie outside its prescribed boundary, and Pr is the probability that at least one such variable is out of bounds. The probability Pr_i was readily computed from the predicted variance of the i^{th} system variable. (Since we considered steady-state conditions, all variables were assumed to be zero-mean Gaussian processes.) "Workload" was represented in the analysis by the attentional variable f_t; the f_i were adjusted to reflect attention-sharing as shown in Table 5. A noise/signal ratio $P_o = 0.01$ was associated with a relative attention of unity. Thus, variations in attentional workload were reflected by changes in the noise/signal ratios according to Eq. (3).

Predictions of performance versus attentional workload are shown in Figure 2 for the eight configurations explored in the BBN study. Values of attention shown on the abscissa are relative to that inferred from data obtained in a standardized laboratory tracking task. That is, unity attention is intended as a benchmark level of workload and does not necessarily relate to maximum effort or capability. Thus, for configurations in which predicted performance is especially sensitive to attention, predictions are shown for relative attentions greater than unity.

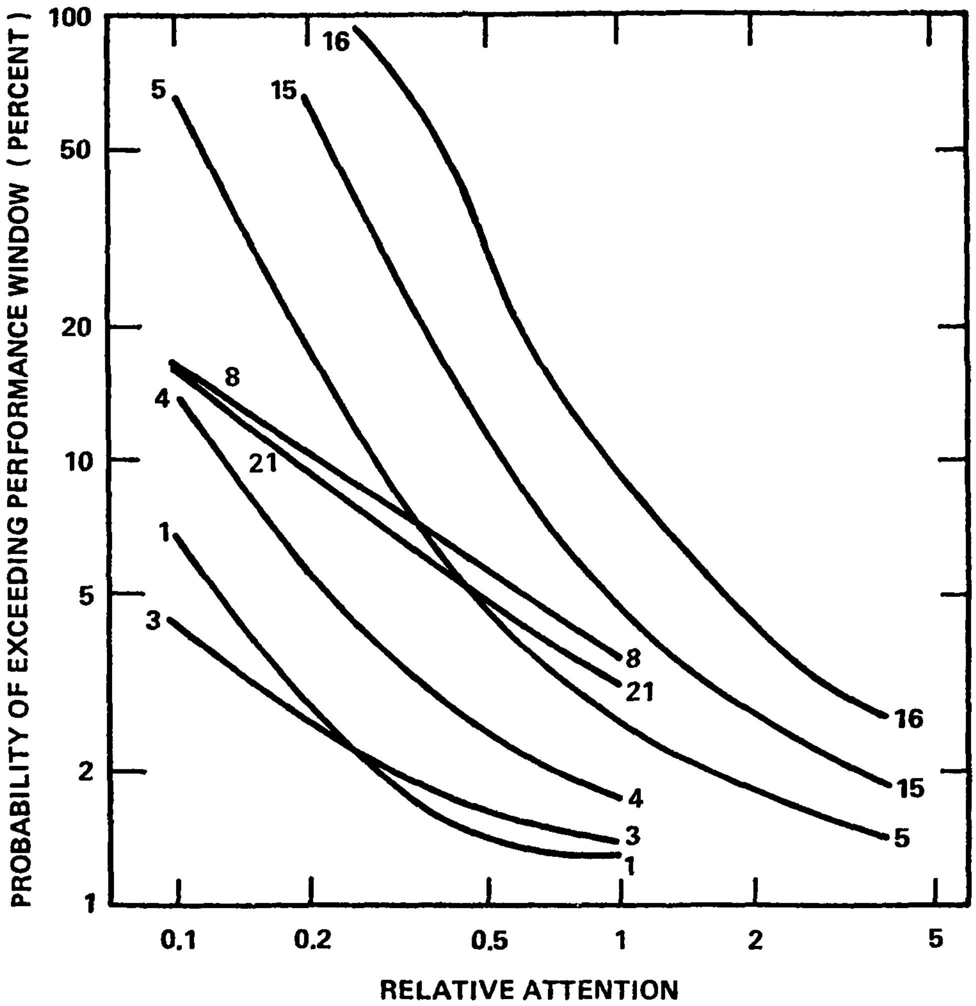


Figure 2. Prediction of Performance versus Workload

The trends shown in Figure 2 are consistent with the pilot ratings given in Table 4. Except for configuration 8, the ordering of the performance/workload curves is consistent with the ordering of the pilot ratings. For attentions of 0.5 and greater, predicted performance for the remaining seven configurations follows the trend of the ratings. Operation on these results to yield predicted pilot ratings is discussed below.

Predicted Ratings

The three rating expressions presented in Figs. (5-7) were applied to the performance/workload tradeoff curves to provide a test of the proposed methodology. Values were assigned to the independent parameters of each expression as shown below in Table 6.

Table 6

Independent Parameters for the Rating Expression

Expression	σ_o	A
Performance Model	5.3%	0.50
Attention Model	5.0%	0.47
Minimum-rating Model	10.0%	2.0

The value of A_o of the performance model was chosen to represent a moderate-to-high workload level, and the corresponding value for σ_o was found through a regression procedure that minimized the mean-squared difference between predicted and experimental pilot ratings, normalized with respect to the variance of each experimental rating. The value for σ_o of the attention model was selected to represent a moderate-to-stringent performance requirement, and the value for A_o was found through a similar regression analysis.

Because of the lack of a tractable analytic expression relating performance to workload, the parameters σ_o and A_o of the minimum-rating model were not found through a computerized regression analysis. Rather, pairs of integers were explored on a trial-and-error basis to provide a good match to experimental pilot ratings. The predicted (minimum) rating for a given configuration was obtained by superimposing the predicted performance/workload tradeoff curve (Figure 2) on the curve of constant rating, shown in Figure 3.

Because of the difficulty in matching the predicted pilot ratings of Configuration 8, ratings for this configuration were omitted from all three regression analyses.

Figure 4 provides a graphical comparison of predicted versus experimental pilot ratings for the three rating expressions. Dashed lines indicate boundaries of $\pm$ 1 rating unit. The three rating schemes performed about equally well on the average and were able to match 6 of the 8 experimental ratings to within one rating unit. The configuration matched least well was Configuration 8, which was omitted from the regression analyses.

Prediction errors may be compared against the variability of the experimental data in Figure 5. Experimental ratings are indicated by filled circles, with brackets to indicate ± 1 standard deviation; open symbols indicate predictions obtained with the three rating expressions.

Except for Configuration 8, predicted ratings are within one standard deviation of the experimental mean. Even for the worst case, the predictin error is well within two standard deviations of the mean. Thus, the reliability of the predicted ratings is commensurate with the reliability of the experimental data.

Discussion of Results

The generally good match between "predicted" and experimental pilot opinion ratings suggests that the model-based approach described in this report is basically valid. The technique is shown to replicate experimental results reasonably well across a set of conditions that spans a range of handling qualities levels and problems. Because the procedure is based on a pilot/vehicle model of considerable generality and demonstrated validity, this scheme ought to be valid for other aircraft configurations and, with appropriate definitions of performance requirements, other flight tasks as well. Further study is required to compare the BBN techniques against other model-based procedures and to further compare the usefulness of the three rating expressions tested in this study.

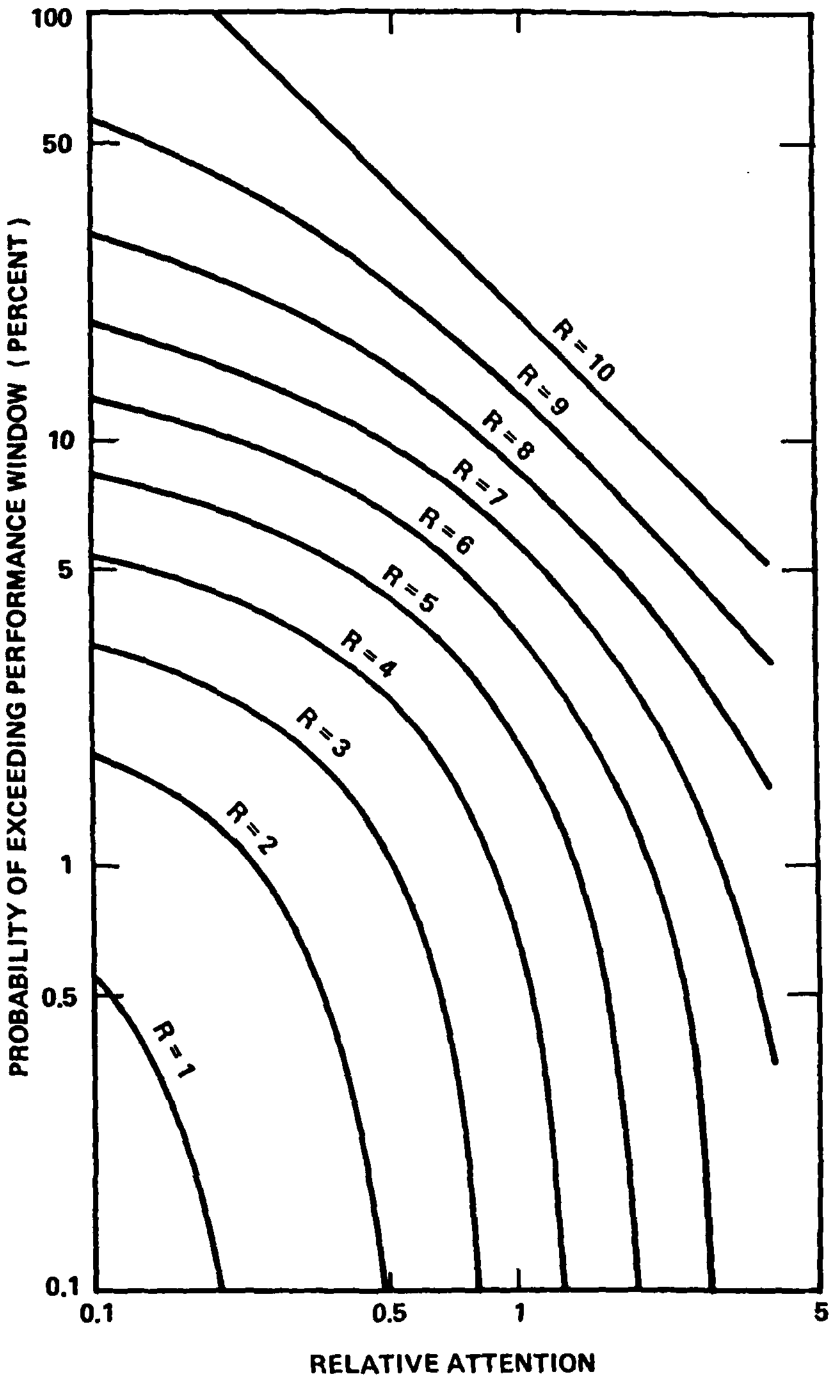


Figure 3. Curves of Constant Rating for the "Minimum Rating" Model

$\sigma_o = 10\%$ $A_o = 2$

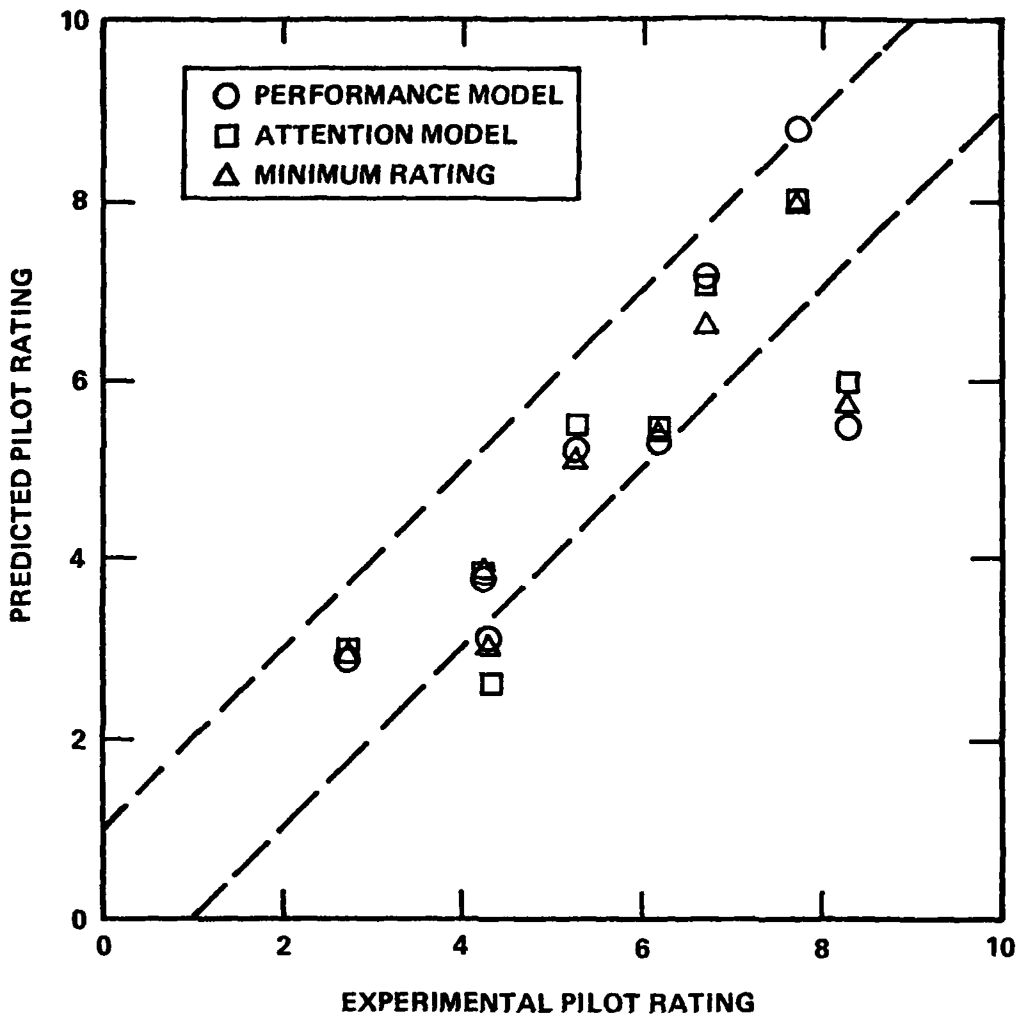


Figure 4. Predicted versus Experimental Pilot Ratings

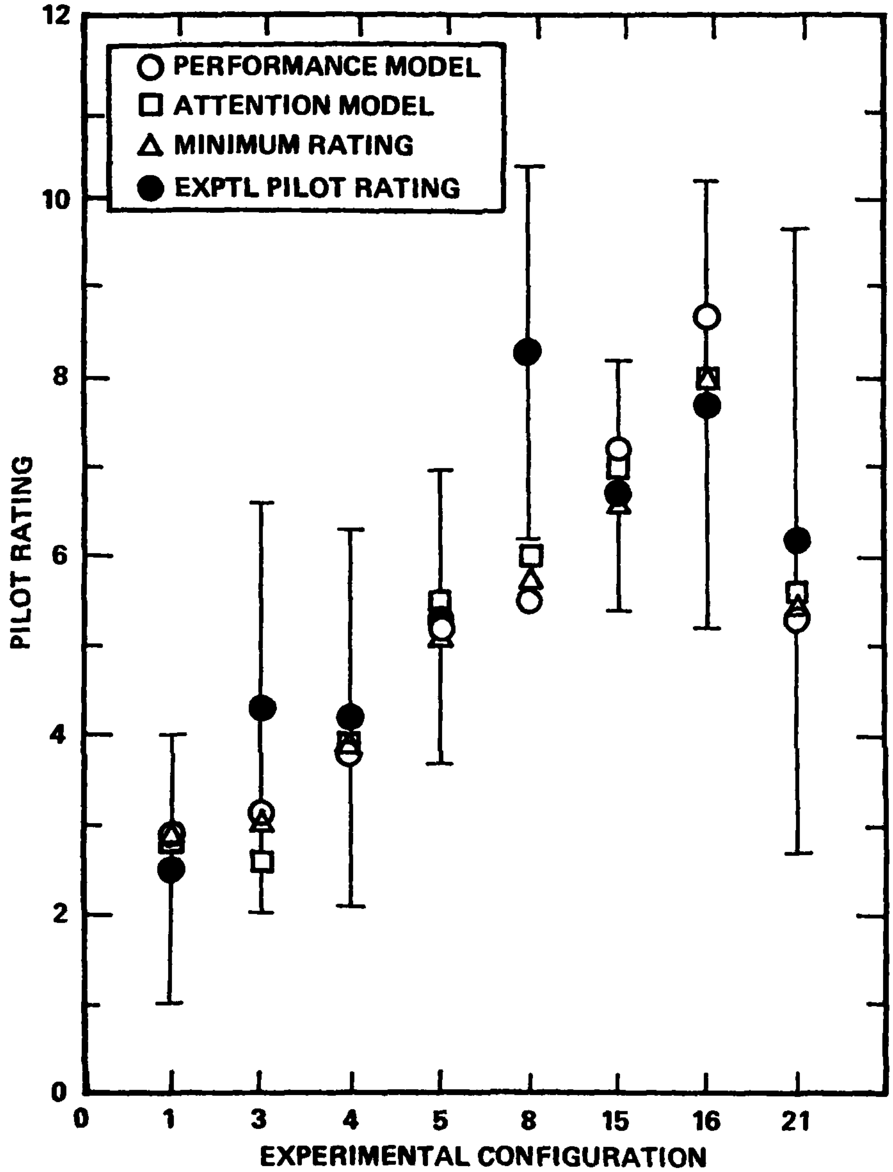


Figure 5. Comparison of Predicted and Experimental Ratings

Resources did not permit a detailed study of the inability to obtain a good match to the experimental rating for Configuration 8. The differences between the average ratings for Configurations 8 and 21 (which our prediction scheme predicts to be negligible) were apparently not due to training effects; these two configurations were presented to the test pilots in a balanced order.

It should be noted that all tests of the proposed methodology have been based on steady-state analysis appropriate to conditions at a single altitude. Although steady-state-like tasks were important determinants of pilot opinion, transient-response behavior was also important. There may have been some aspects of glide-slope capture and other transient maneuvers that were especially adverse for Configuration 8. Additionally, it is possible that a different choice of steady-state parameters (e.g., turbulence appropriate to a lower altitude, different "limits" on throttle response) may have differentiated between Configuration 8 and 21.

Data from the Douglas experiments were used in the BBN study because of their applicability to large transports. Because the experimental study was performed well before the BBN analytical study, the Douglas effort was not designed to allow a thorough test of the model-based prediction to scheme. Hindsight reveals the following methodological deficiencies:

1. Sparcity of Performance Measurements. Pilot opinion ratings were the only data published relating to closed-loop pilot/vehicle performance. Objective performance measures such as rms errors, pilot describing functions, spectra, or time histories are not available. Thus, we cannot determine the pilot's "operating point" in terms of pilot-related model parameters, and we cannot verify the ability of the model to predict objective performance measures.

2. Large Rating Variability. Standard deviations for pilot ratings, as determined across subjects, were relatively large, reaching a maximum of 3.5. Clearly, large variability in the data hinders a rigorous test of the prediction scheme. To some extent, the large standard deviations resulted from a small subject population (only 3 subjects provided ratings for four of the configurations explored in the BBN study). As described below, a more significant factor may have been an insufficiently specific evaluation procedure.

3. Insufficiently Specific Evaluation Procedure. Typically, each pilot was allowed two "flights" per configuration: an initial flight without turbulence, and a follow-up flight with moderate turbulence. The pilots were encouraged to perform maneuvers that would aid in developing their rating, and they were asked for a single overall rating of the configuration of the end of the two flights. While all subjects appeared to consider the same basic maneuvers and subtasks (glide-slope capture, glide-slope tracking, recover from mistrim, open-loop vehicle response), we do not know the extent to which each pilot weighted the various response categories. Different weightings might have led to different ratings for the same configuration -- a possible explanation for the large pilot-to-pilot variability observed in this study. Differences in the pilot's expectations of system performance are an additional potential source of rating variability.

Consideration of these methodological shortcomings suggests alternative approaches in future studies, as outlined below.

CONCLUSIONS AND RECOMMENDATIONS

A technique based on the optimal-control model for pilot/vehicle systems has been developed for predicting pilot opinion ratings. Three variations of this technique provide a good match to opinion ratings obtained in a manned simulation study of large commercial transports in landing approach.

The model-based technique developed in this study has a number of features which should enhance its applicability to other aircraft configurations and other flight tasks and should allow wider application than alternative handling qualities prediction schemes:

1. One is able to proceed in a straightforward manner from a description of the task environment and of task requirements to a prediction of pilot opinion ratings. The general form of the rating expression and of the underlying pilot model is invariant across applications.

2. No constraints are placed on the nature of the vehicle response, and the pilot model is relatively free form. Thus, "unconventional" aircraft dynamics may be considered.

3. A scalar metric for attentional workload is expressed in terms of a model parameter related to the signal/noise properties of the pilot's response. Thus, the treatment of workload is independent of the details of the flight task.

4. The effects of display parameters, turbulence, and other environmental factors on pilot opinion rating are readily considered.

Encouraging results obtained with the model-based technique tested in this study warrant further research to provide a more rigorous test of the procedure and to determine its range of validity. Such a study should be subjected to the following guidelines:

1. Flight Test Standardization. The flight tests performed for the purpose of obtaining pilot opinion ratings should be standardized so that all pilots perform the same maneuvers on the aircraft. Either separate ratings should be obtained for individual maneuvers, or care should be taken to assure that all pilots weight the various maneuvers in the same manner when assigning an overall rating to the aircraft.

2. Define Performance Criteria. Through a carefully prepared and administered questionnaire, subjective performance criteria should be determined for the various test maneuvers. If practical, test pilots should be encouraged to adopt a common set of criteria to minimize rating variability.

3. Performance Measurement. Objective measures of system performance and pilot response behavior should be obtained in addition to pilot opinion ratings to provide a more rigorous test of the method.

REFERENCES

1. Levison, W. H., "A Model-Based Technique for Predicting Pilot Opinion Rating for Large Commercial Transports", Report No. 4153, Bolt Beranek and Newman Inc., Cambridge, Massachusetts, July 1976.

2. "Flying Qualities of Piloted Airplanes", Military Specification, MIL-F-8785B (ASG), 1969.

3. Neal, T. P. and R. E. Smith, "An In-Flight Investigation to Develop Control System Design Criteria for Fighter Airplanes", Wright-Patterson Air Force Base, Ohio, Volume I, AFFDL-TR-70-74, 1970.

4. Anderson, R. O., "A New Approach to the Specification and Evaluation of Flying Qualities", Wright-Patterson Air Force Base, AFFDL-TR-69-120, 1970.

5. Arnold, J. D., R. B. Johnson, and J. D. Dillow, "Pitch Paper Pilot Revisited", Proceedings of the Ninth Annual Conference on Manual Control, Massachusetts Institude of Technology, Cambridge, Massachusetts, 1973.

6. Naylor, F. R., J. D. Dillow, and R. A. Hannen, "Roll Paper Pilot", Proceedings of the Ninth Annual Conference on Manual Control, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1973.

7. Stone, J. R., "Paper Pilot Ponders Supersonic Transports", Proceedings of the Ninth Annual Conference on Manual Control, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1973.

8. Hess, R. A., "Prediction of Pilot Opinion Ratings Using an Optimal Pilot Model", HUMAN FACTORS, 1977, 19(5), 459-475.

9. Kleinman, D. L., S. Baron and W. H. Levison, "An Optimal Control Model of Human Response, Part 1: Theory and Validation", Automatica, Vol. 6, 1970.

10. Kleinman, D. L., S. Baron and W. H. Levison, "A Control Theoretic Approach to Manned-Vehicle Systems Analysis", IEEE Trans. on Auto. Control, Vol. AC-16, No. 6, Dec. 1971.

11. Schmidt, D. K., "Optimal Flight Control Synthesis via Pilot Modeling", Journal of Guidance and Control, Vol. 2, No. 4, Jul.-Aug. 1979.

12. Levison, W. H., J. I. Elkind and J. L. Ward, "Studies of Multi-Variable Manual Control Systems: A Model for Task Interference", NASA CR-1746, May 1971.

13. Levison, W. H., "The Effects of Display Gain and Signal Bandwidth on Human Controller Remnant", Wright-Patterson Air Force Base, Ohio, AMRL-TR-70-93, March 1971.

14. Zacharias, G. L. and W. H. Levison, "A Performance Analyzer for Identifying Changes in Human Operator Tracking Strategies", AMRL-TR-79-17, March 1979.

15. Kleinman, D. L. and S. Baron, "Analytic Evaluation of Display Requirements for Approach to Landing", NASA CR-1952, Nov. 1971.

16. Kleinman, D. L. and W. R. Killingsworth, "A Predictive Pilot Model for STOL Aircraft Landing", NASA CR-2374, March 1974.

17. Levison, W. H., "Analysis and In-Simulator Evaluation of Display and Control Concepts for a Terminal Configured Vehicle in Final Approach in a Windshear Environment", NASA Contractor Report 3034, August 1978.

18. Levison, W. H., S. Baron, and A. M. Junker, "Modeling the Effects of Environmental Factors on Human Control and Information Processing", AMRL-TR-76-74, August 1976.

19. Lancraft, R. E., and D. L. Kleinman, "On the Identification of Parameters in the Optimal Control Model", Fifteenth Annual Conference on Manual Control, Wright State University, Dayton, Ohio, March 20-22, 1979.

20. Baron, S. and W. H. Levison, "Display Analysis with the Optimal Control Model of the Human Operator", HUMAN FACTORS, 1977, 19(5) 437-457.

21. Levison, W. H., "A Model forMental Workload in Tasks Requiring Continuous Information Processing", Mental Workload Its Theory and Measurement, Plenum Press, New York and London, 1979.

22. Wewerinke, P. H., "Human Operator Workload for Various Control Situations", Tenth Annual Conference on Manual Control, Wright-Patterson Air Force Base, Ohio, 1974.

23. Volkman, F. C., A. M. L. Schick, and L. A. Riggs, "Time Course of Visual Inhibition During Voluntary Saccades", Jl. Opt. Soc. Am., 58, pp. 562-569, 1968.

24. Cooper, G. E., "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities", NASA TN D-5153, April 1969.

25. Rickard, W. W., "Longitudinal Flying Qualities in the Landing Approach", Proceedings from the Twelfth Annual Conference on Manual Control, NASA TMX-73,170, May 1976.

26. Levison, W. H., S. Baron, "Analytic and Experimental Evaluation of Display and Control Concepts for a Terminal Configured Vehicle", Report No. 3270, Bolt Beranek and Newman Inc., Cambridge, Massachusetts, July 1976.

27. Baron, S. and W. H. Levison, "A Manned Control Theory Analysis of Vertical Situation Displays for STOL Aircraft", NASA CR-114620, April 1973.

APPROACH AND LANDING FLYING QUALITIES REQUIREMENTS

By

Robert C. Radford

and

Rogers E. Smith

Calspan Corporation
Flight Research Branch
Flight Sciences Department
Buffalo, New York 14225

The purpose of this presentation is to describe the results, to date, of a study of flying qualities criteria for augmented aircraft in the landing approach flight phase. This effort was sponsored by the NASA Dryden Flight Research Center.

The scope of the study precluded the development of new criteria. Instead, the approach taken was to select several existing criteria and apply these to the data of the LAHOS experiment (AFFDL-TR-78-122). The criteria selected and the source or reference documents for each are presented in the first vu-graph.

The choice of criteria was motivated, in part, by the fact that each criterion has been applied to the same data base (Neal-Smith, AFFDL-TR-70-74) with generally good results. Furthermore these criteria represent a good cross-section of methodologies (i.e. open versus closed loop and time domain versus frequency domain criteria).

"NASA DFRC FLYING QUALITIES REQUIREMENTS"

PRESENTATION OUTLINE

- Summary of LAHOS* Experiment
- Flying Qualities Criteria Survey and Application to LAHOS Data
  - (1) R. H. Smith (AFFDL-TR-77-57, AFFDL-TR-79-71, NASA Houston Briefing Handout)
  - (2) Neal-Smith (AFFDL-TR-70-74)
  - (3) E. Onstott (AFFDL-TR-78-3)
- Conclusions, Recommendations

* "Landing Approach Higher Order Systems" Sponsored by AFFDL

REVIEW OF LAHOS EXPERIMENT

- Motivated largely by experience during NT-33 in-flight simulation of YF-17 aircraft prior to first flight.

  - discovered severe pitch PIO problems in the approach and landing task; in particular close to the runway.

  - these problems were not predicted by MIL SPEC, sophisticated ground simulations, or a version of the Neal-Smith criteria with a low assumed bandwidth.

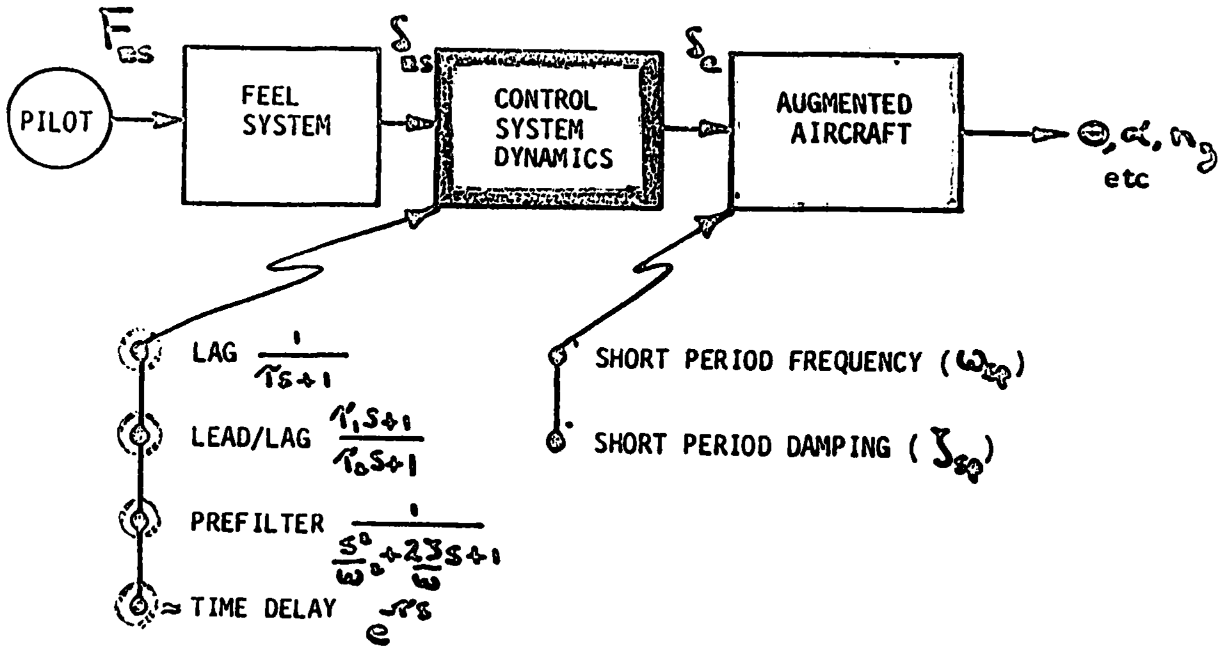
- Accordingly, the experiment variables selected for the experiment were: short period frequency and damping ratio and representative control system dynamics ranging from simple first order lags to time delays (mechanized as a fourth-order Butterworth filter).

- The task involved visual and instrument approaches and typically actual touchdowns.

  - pilot comments and ratings were obtained for the overall task as well as the approach alone.

  - selected configurations were evaluated without touchdowns.

EXPERIMENT VARIABLES



o $M_{\delta_{es}}$ (PILOT SELECTED)

COMPARISON OF PRIMARY LAHOS CONFIGURATIONS WITH -8785B

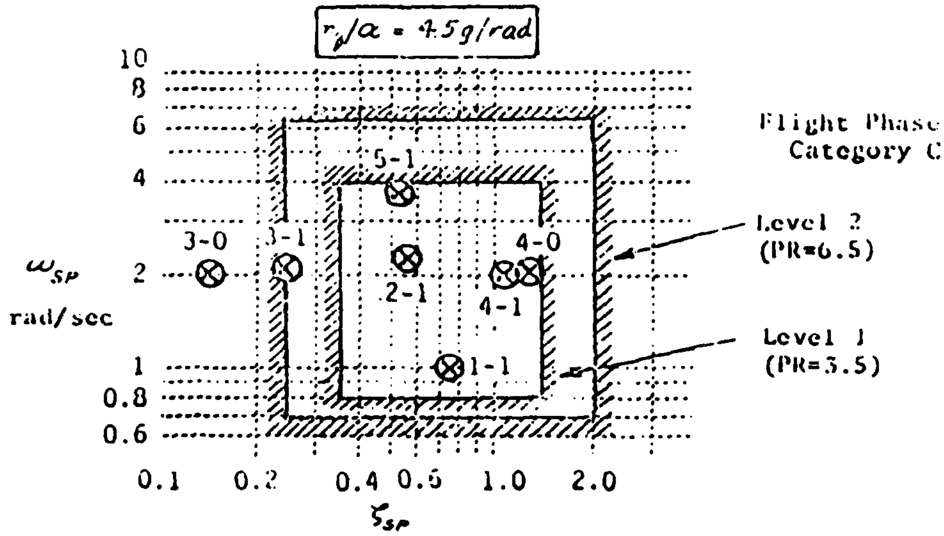
- In addition to these configurations, the LAHOS experiment included simulation of:

  - YF-17 with original flight control system (Config. 6-1),

  - YF-17 with modified flight control system, as flown on first flight (Config. 6-2),

  - 3 statically unstable aircraft with time to double amplitude ranging from 2 to 6 seconds. (Config. 7-1, 7-2, 7-3).

- V_{ind} = 120 knots
- V_T = 205 ft/sec
- n_z/α = 4.5 g/rad
- τ_{θ_2} = 1.4 sec
- $1/\tau_{\theta_2}$ = 0.7 rad/sec



COMPARISON OF PRIMARY SHORT PERIOD CONFIGURATIONS WITH MIL-F-8785B

RALPH SMITH CRITERION

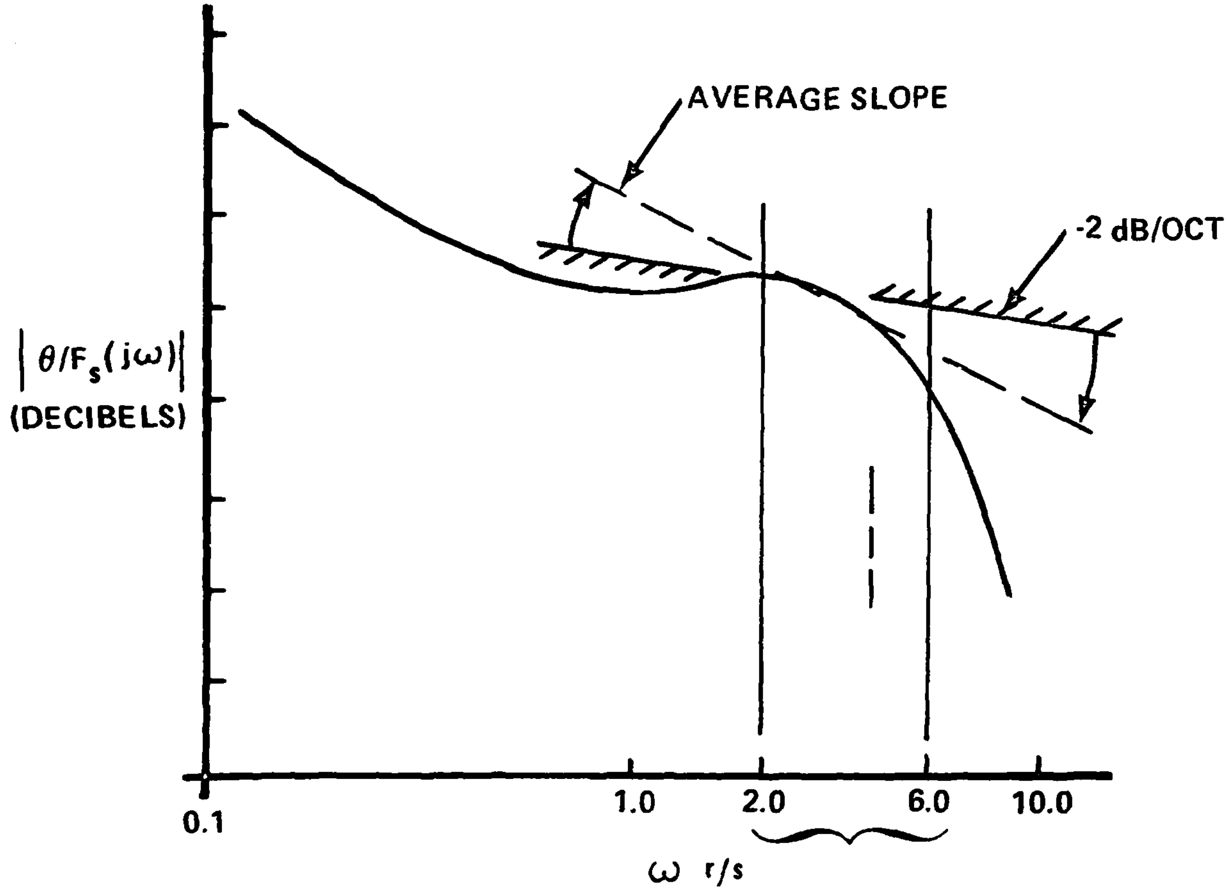
- Discussion limited to mechanics of applying criterion within the context of the cited reference documents (Vu-graph 1).

- Central to the application of the criterion is the calculation of the criterion frequency which requires determination of the average slope as shown. A simple average was used based on the values at 2 and 6 rad/sec. (Recently published guidelines use a different method involving a weighted average of slopes over the interval).

- When applied to the original Neal-Smith data base, pilot rating was a strong function of the phase angle of the pitch attitude to stick force transfer function at the criterion frequency.

- Data on prediction of PIO rating is not presented because in this experiment the normal acceleration at the pilot's station was considered to be too low to be a primary mechanisim in a PIO.

ILLUSTRATION OF CRITERION FREQUENCY CALCULATION (R. H. SMITH)



CRITERION FREQUENCY:

$$\boxed{\omega_c = 0.24 \times \text{SLOPE} + 6.24}$$

R. SMITH CRITERION APPLIED TO LAHOS DATA

- In a previous correlation, all the Neal-Smith data fit between the solid boundaries shown.

- Criterion in its present form is not applicable.

- Flags designate configurations which fail a supplementary criterion on time to maximum pitch rate.

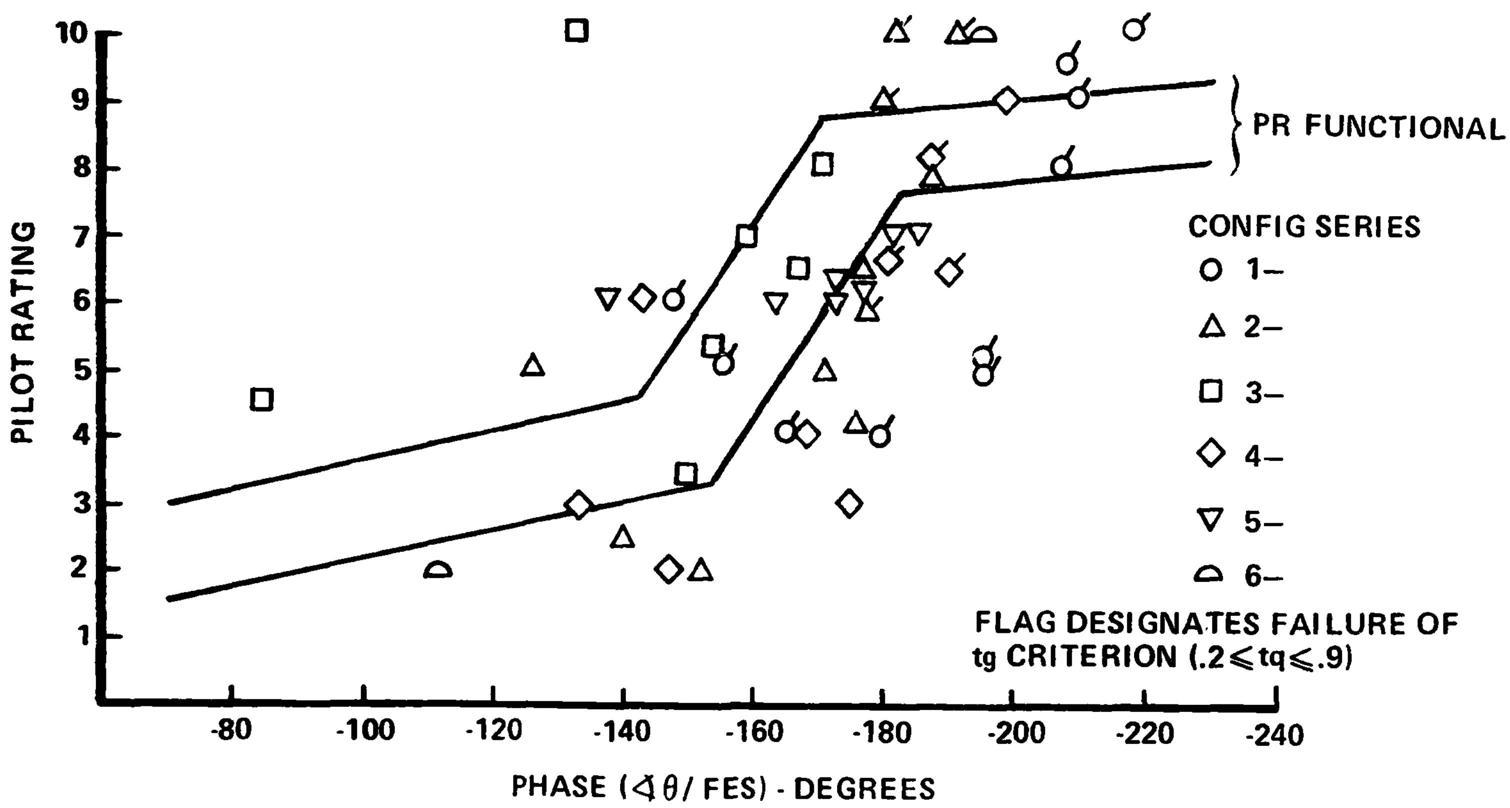
- Conclusions

  - does a good job on YF-17 configuration (Config. 6-1, 6-2).

  - there is a trend but scatter is high.

  - a more careful study is required to find best parameters for the LAHOS data base.

ATTITUDE PHASE CRITERION APPLIED TO LAHOS DATA

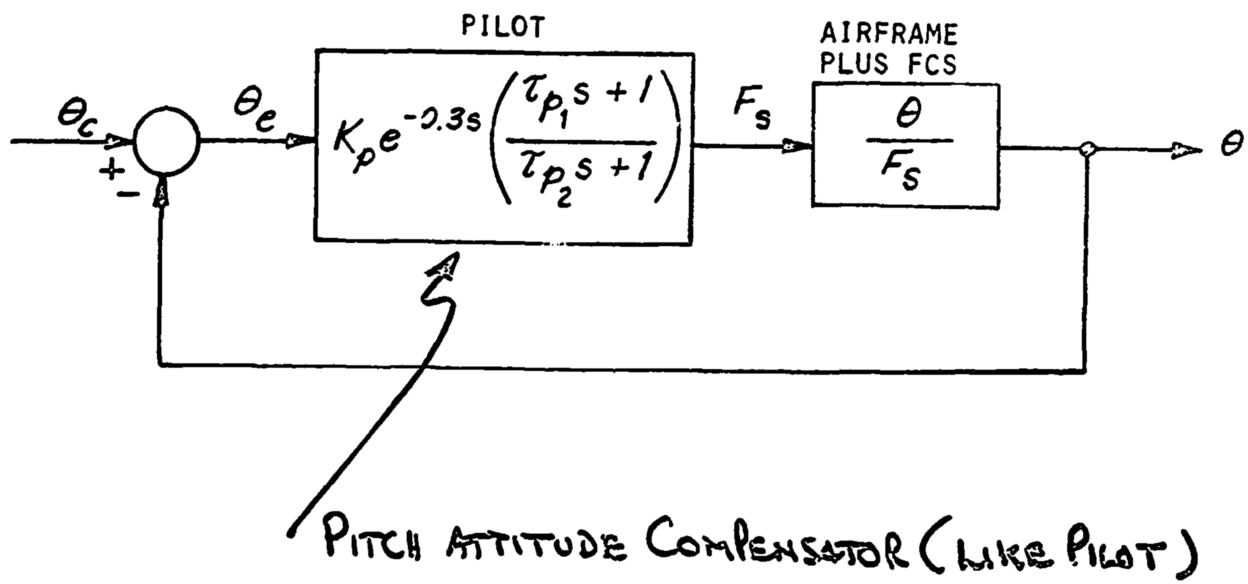


APPLICATION OF NEAL-SMITH CRITERION TO LAHOS DATA

- Although a pilot model block is used in the criterion it is more appropriate to view this block as a "Pitch Attitude Compensator". The form of the pitch compensator is representative of pilot models but is not necessarily an accurate description of actual pilot behaviour.

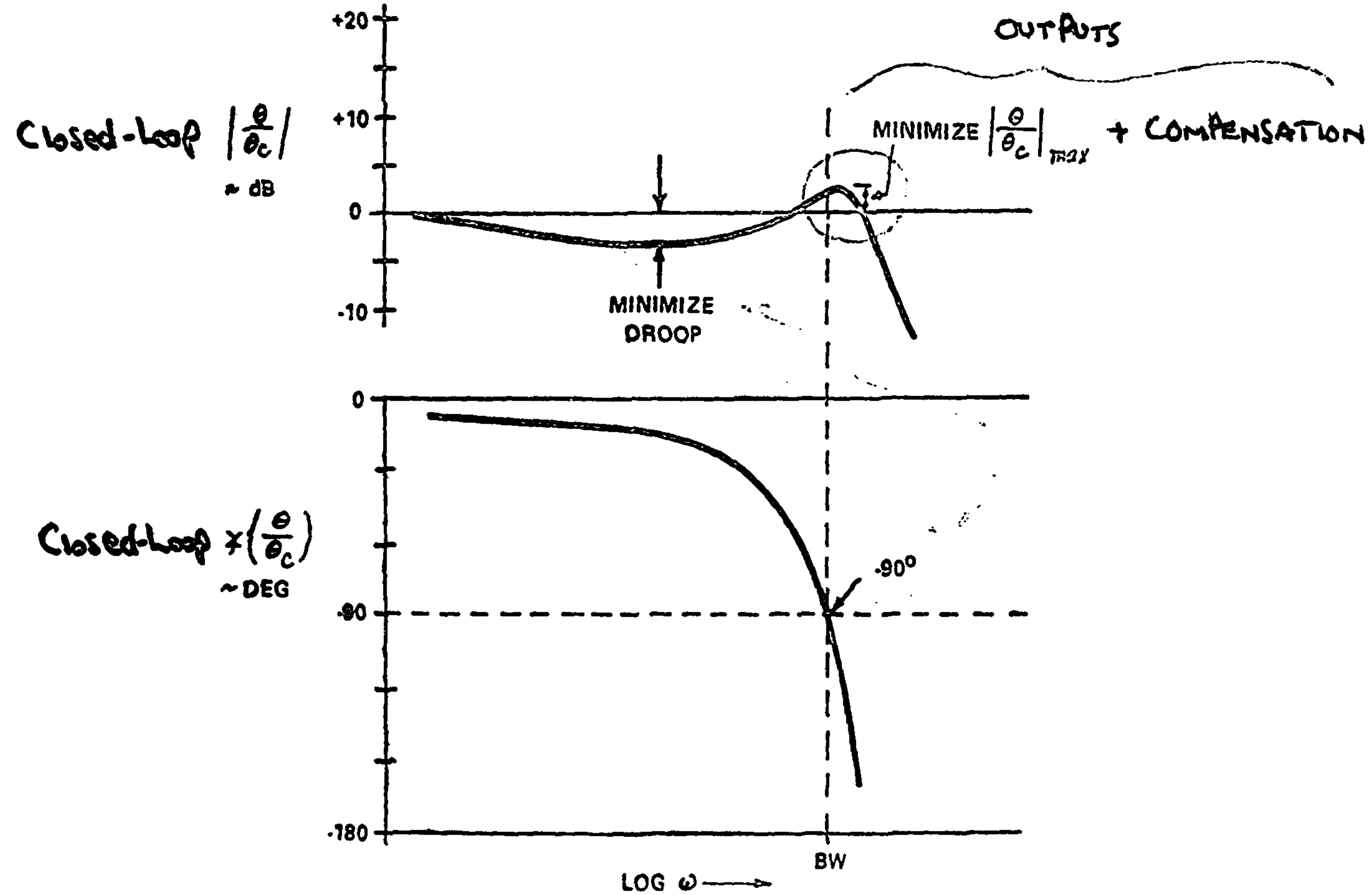
- With the original data base, the criterion was a good "flying qualities yardstick".

CRITERION PITCH ATTITUDE TRACKING TASK



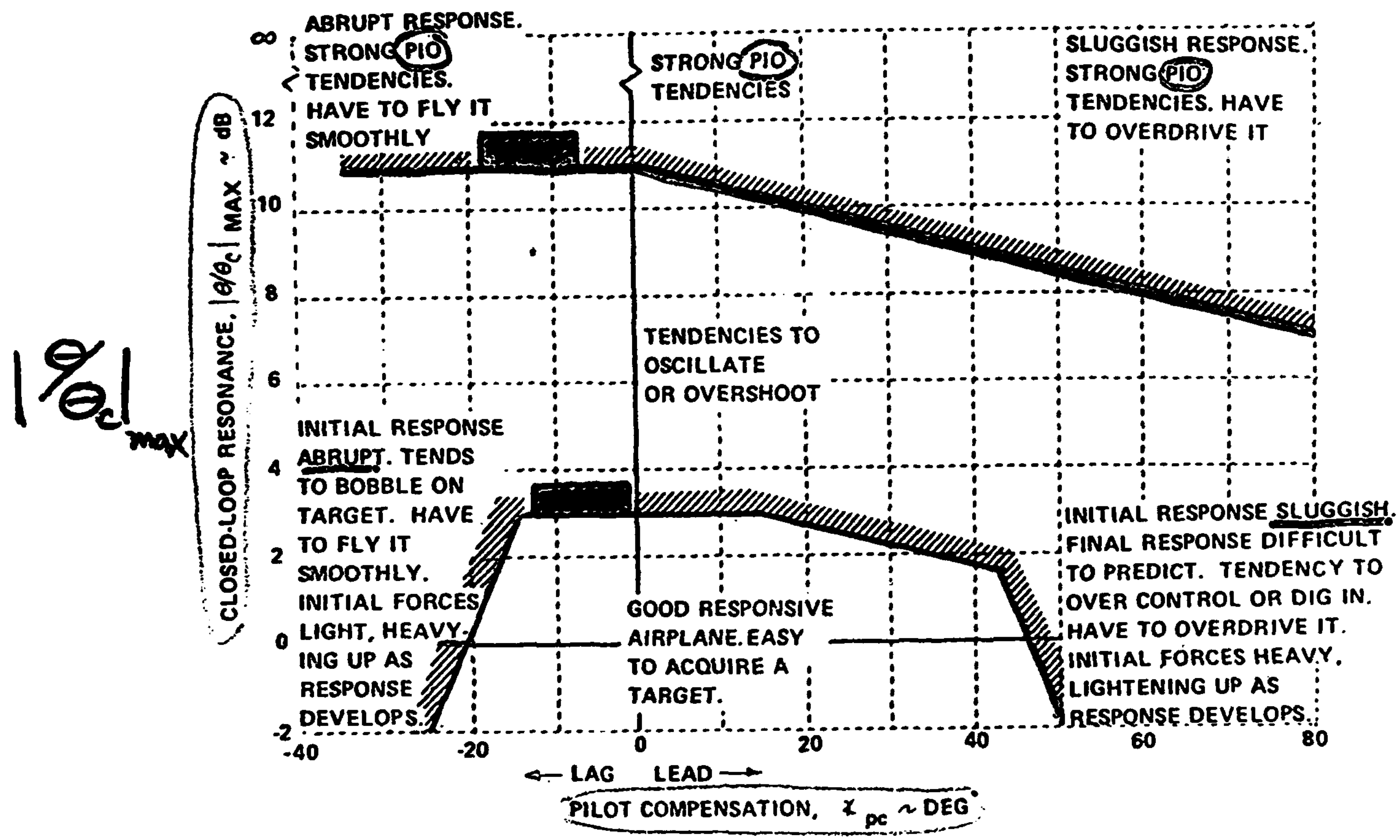
NEAL-SMITH CRITERION PARAMETERS

- Defines pitch attitude tracking performance parameters: closed-loop bandwidth, droop, and maximum resonance (Reference AFFDL-TR-70-74).


OUTPUTS
Closed-Loop $\left|\frac{\theta}{\theta_c}\right|$ ~ dB
+20
+10
0
-10
MINIMIZE $\left|\frac{\theta}{\theta_c}\right|_{max}$ + COMPENSATION
MINIMIZE DROOP
Closed-Loop $\angle\left(\frac{\theta}{\theta_c}\right)$ ~DEG
0
-90
-180
-90°
BW
LOG ω

NEAL-SMITH PARAMETER PLANE

- Illustrates pilot rating boundaries in Neal-Smith parameter plane and typical pilot comments. Coordinates are maximum closed-loop resonance and pilot compensation required (phase angle at the bandwidth frequency).



$|\theta/\theta_c|_{max}$
CLOSED-LOOP RESONANCE, $|\theta/\theta_c|$ MAX ~ dB
∞
12
10
8
6
4
2
0
-2
-40
-20
0
20
40
60
80
← LAG LEAD →
PILOT COMPENSATION, τ_{pc} ~ DEG
ABRUPT RESPONSE. STRONG PIO TENDENCIES. HAVE TO FLY IT SMOOTHLY
STRONG PIO TENDENCIES
SLUGGISH RESPONSE. STRONG PIO TENDENCIES. HAVE TO OVERDRIVE IT
TENDENCIES TO OSCILLATE OR OVERSHOOT
INITIAL RESPONSE ABRUPT. TENDS TO BOBBLE ON TARGET. HAVE TO FLY IT SMOOTHLY. INITIAL FORCES LIGHT, HEAVYING UP AS RESPONSE DEVELOPS.
GOOD RESPONSIVE AIRPLANE. EASY TO ACQUIRE A TARGET.
INITIAL RESPONSE SLUGGISH. FINAL RESPONSE DIFFICULT TO PREDICT. TENDENCY TO OVER CONTROL OR DIG IN. HAVE TO OVERDRIVE IT. INITIAL FORCES HEAVY, LIGHTENING UP AS RESPONSE DEVELOPS.

ITERATION OF CRITERION TO FIT LAHOS DATA

- Application of criterion with low bandwidth as suggested in Reference AFFDL-TR-72-41 doesn't work since landing task is clearly a higher bandwidth task (YF-17 example).

- Tried the same bandwidths derived in Neal-Smith report for fighter tracking; correlation was better but significant anomalies were present.

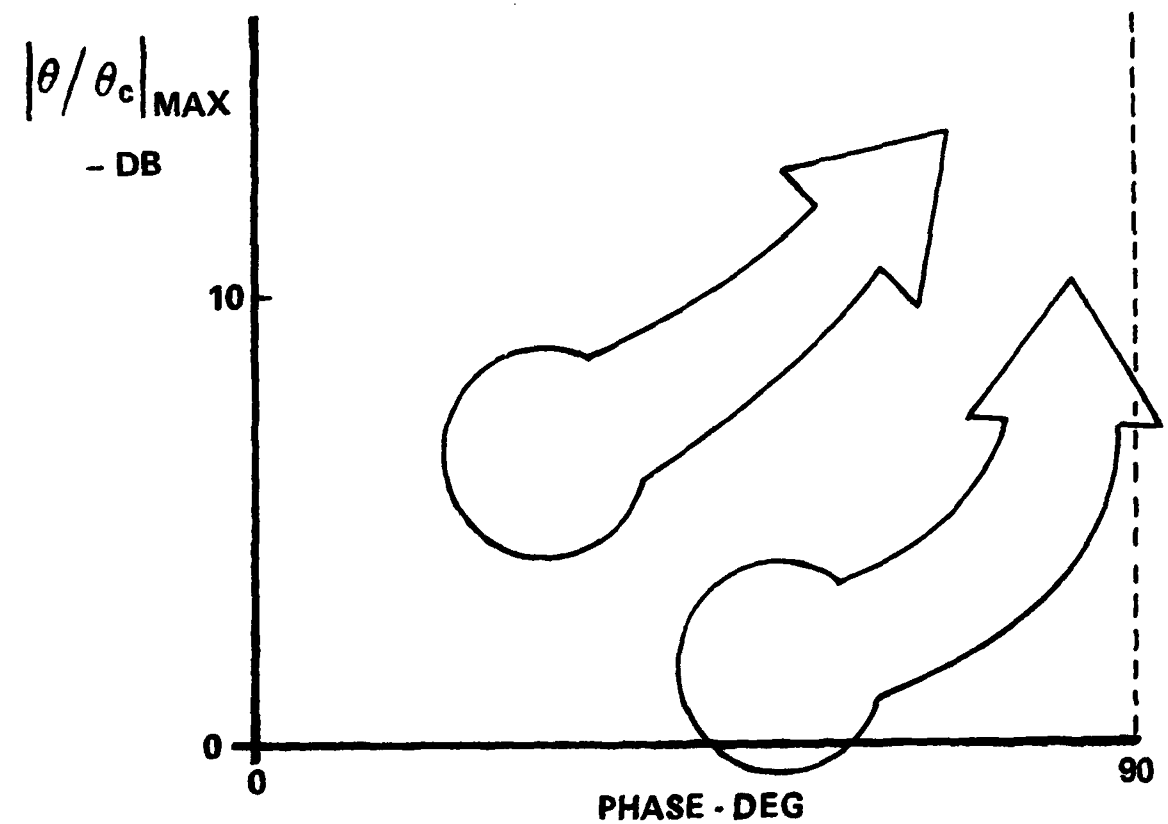
- Decided to take a "fresh" look at criterion parameters for analysis of LAHOS data (varied bandwidth and pilot time delay seek best correlation of data).

- Centered our attention on good "benchmark" configurations: Configs 2-1, Config 6-2 (YF-17).

  - objective was to have these configurations in sensible locations on criterion plane and simultaneously provide discrimination of the remaining data

  - used pilot ratings, comments, and tracking records for guidance.

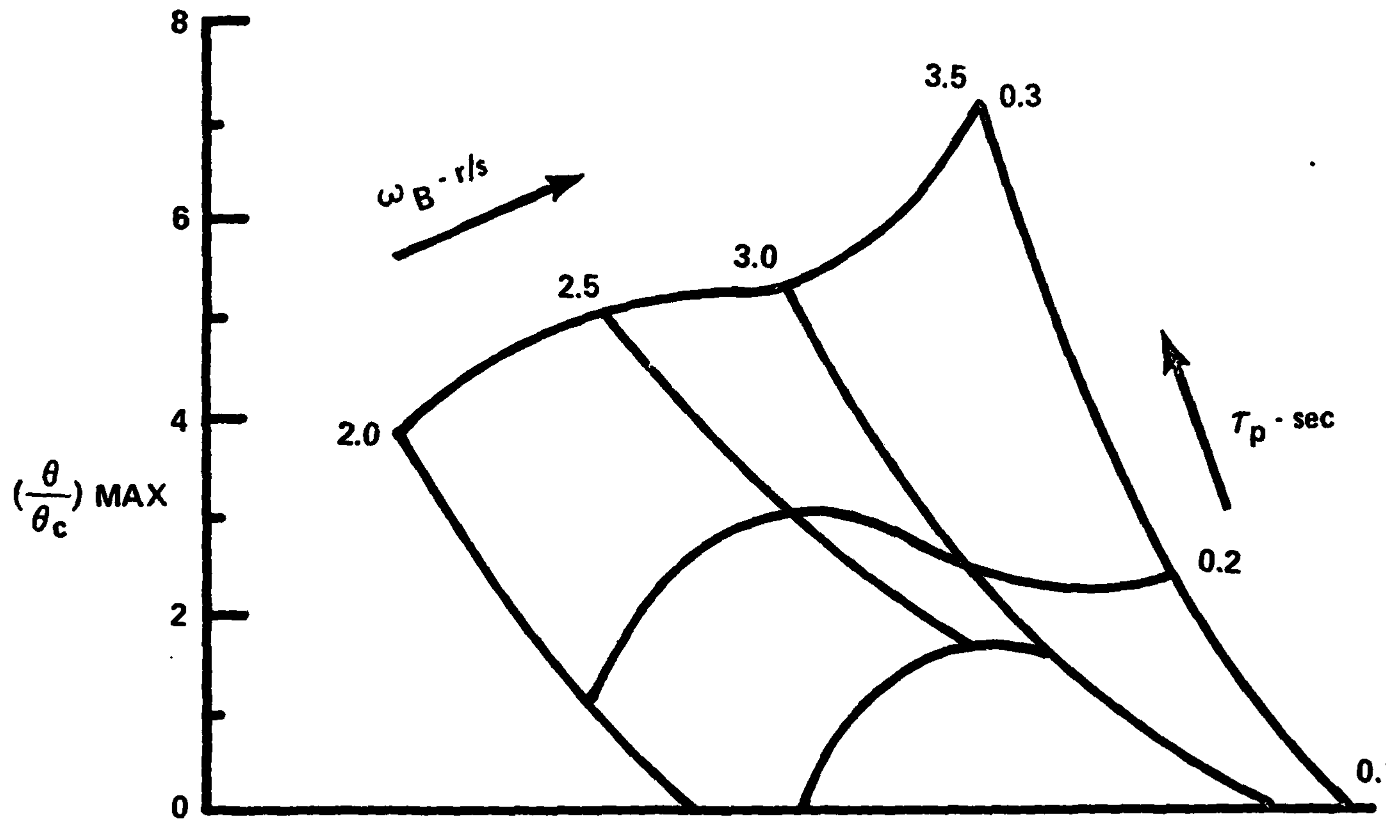
EFFECT OF INCREASED BANDWIDTH ON CONFIGURATION MAPPING IN NEAL-SMITH PARAMETER PLANE



EFFECT OF PILOT TIME DELAY AND BANDWIDTH ON CLOSE LOOP RESONANCE

- Pilot comments, ratings and tracking data indicated that Config 2-1 exhibited well damped closed loop performance.
- Could not achieve reasonable closed loop resonance through bandwidth variations with pilot time delay of 0.3.
- Reducing assumed pilot time delay to 0.2 produced reasonable closed loop resonance for 2-1 and other "benchmark" configuration (6-2).

VARIATION OF $(\theta/\theta_c)_{MAX}$ WITH BANDWITH (ω_B) AND PILOT TIME DELAY (τ_p) FOR LAHOS CONFIGURATION 2-1



SUMMARY OF LAHOS DATA IN NEAL-SMITH PARAMETER PLANE

- Plot summarizes data for bandwidth of 3.0 rad/sec and pilot time delay of 0.2 sec.

- Grouping of data by pilot rating is comparable to original Neal-Smith analysis.

- Configurations with negative resonance are a consequence of forcing the "droop" requirement.

- The 3- series configurations (low short period damping) are not included; the baseline configurations (3-0 and 3-1) cannot be correlated using these revised criterion constraints. Analysis of these configurations is not yet complete.

LAHOS DATA $B\omega = 3.0$ r/s, $t_p = 0.2$

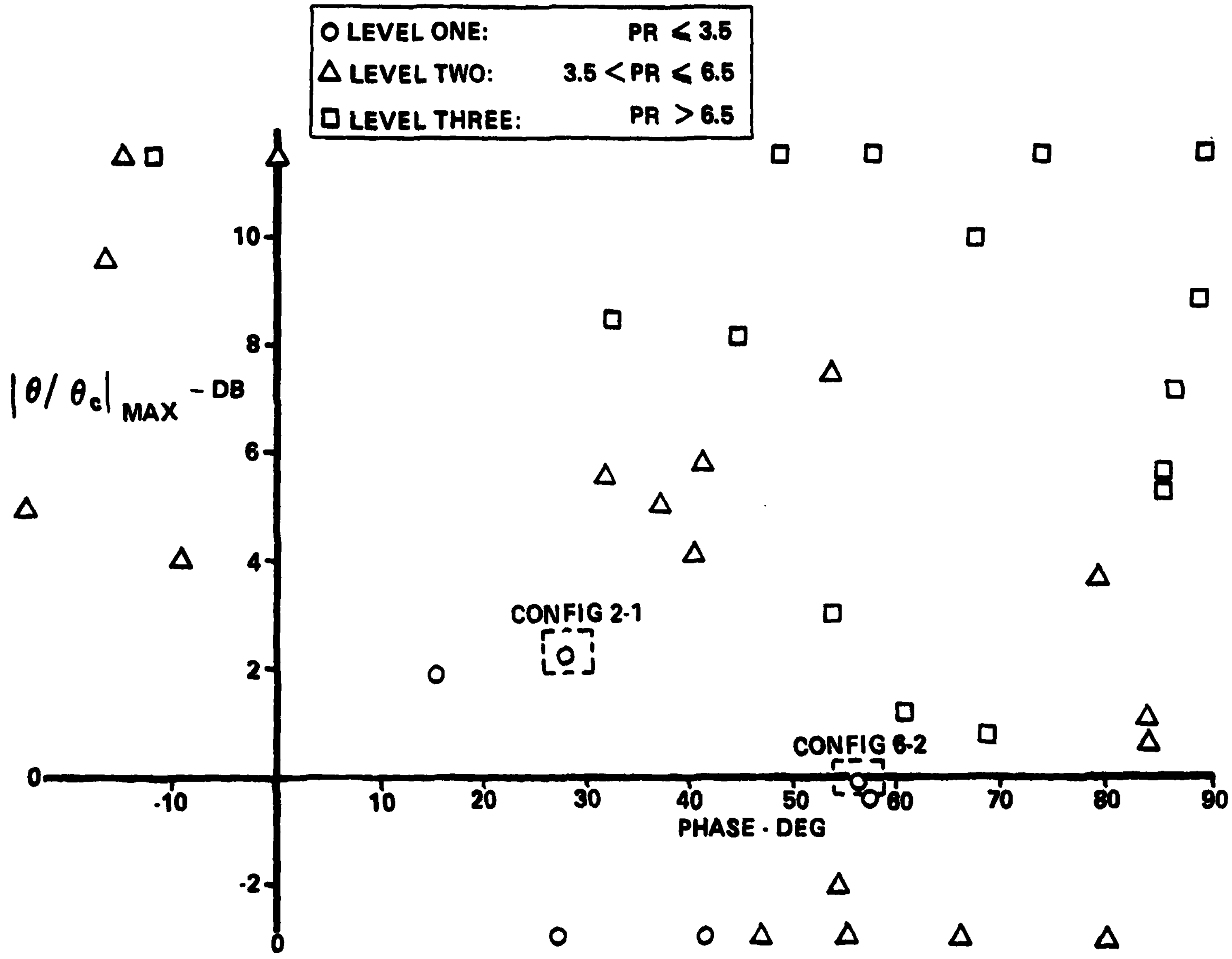
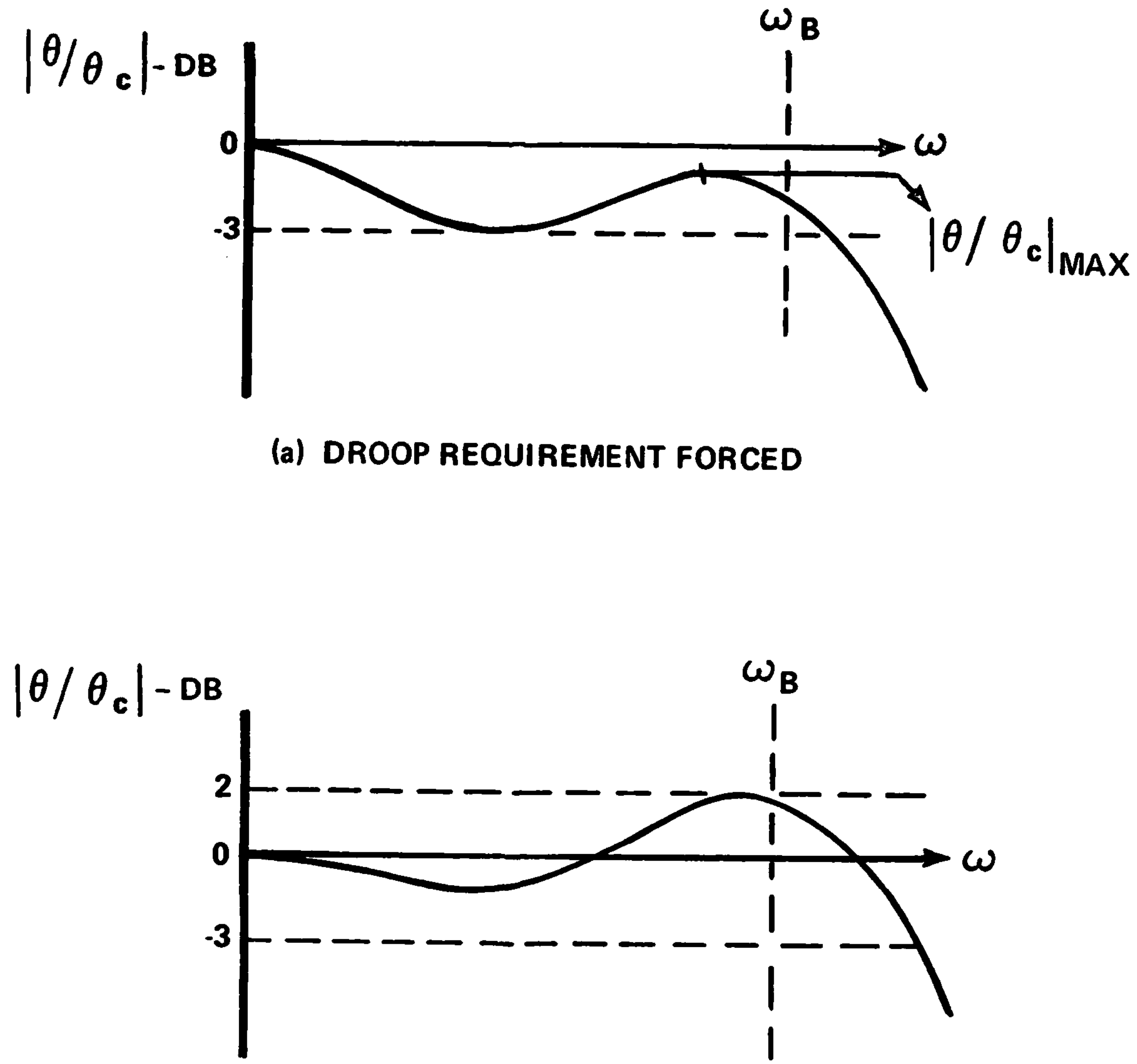


ILLUSTRATION OF EFFECT OF DROOP REQUIREMENT

ON CONFIGURATIONS WITH LOW RESONANCE

- This change was incorporated to correlation and to make the compensation required to meet the desired bandwidth more realistic.

EFFECT OF DROOP REQUIREMENT ON LOW RESONANCE CONFIGURATIONS

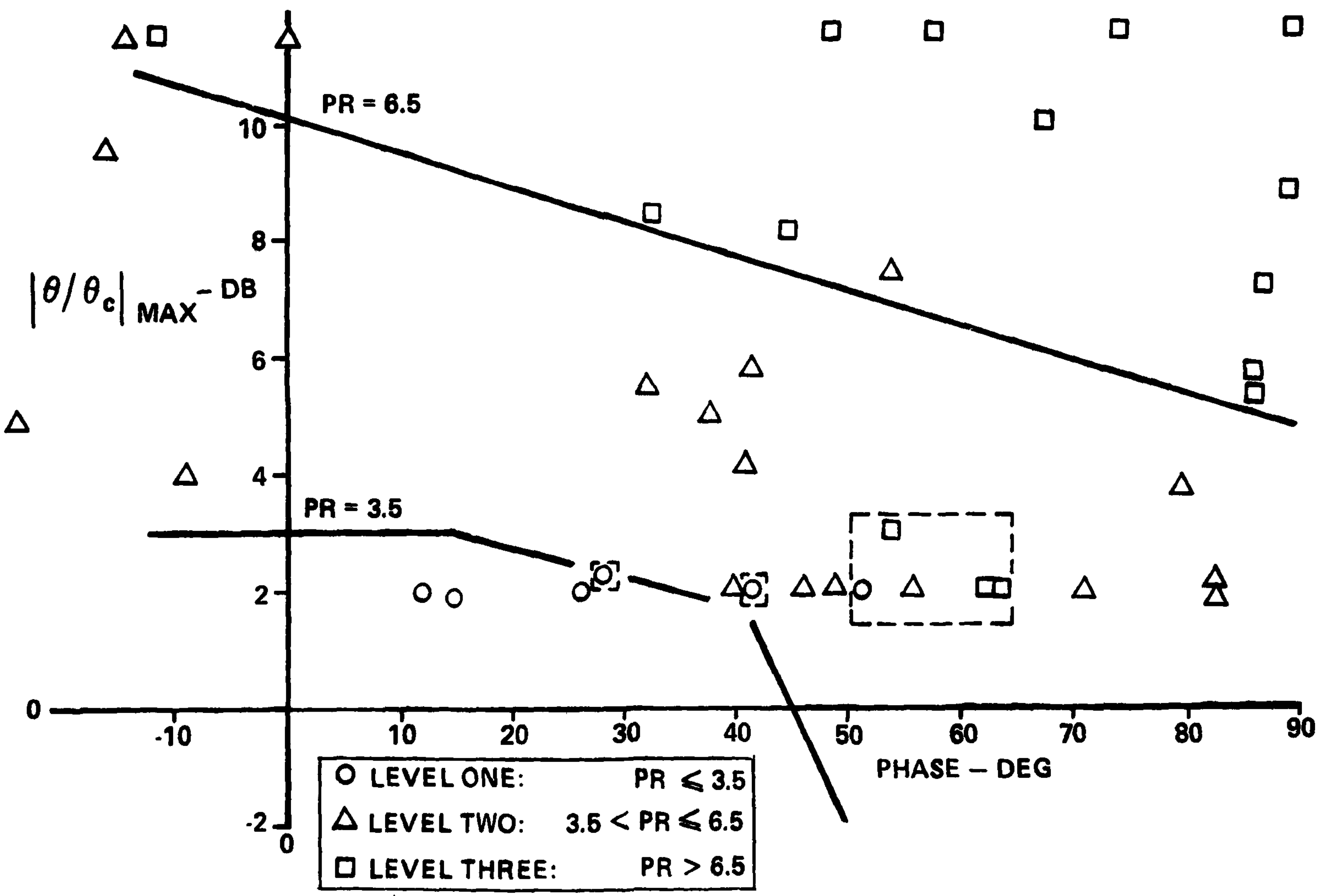


(b) DROOP REQUIREMENT RELAXED

FINAL CORRELATION OF LAHOS DATA

- Configurations 3- and 7- not included. Only Config 3-0 and 3-1 present a problem.
- "3½" boundary the same as original Neal-Smith; "6½" boundary slightly modified.
- Correlation is good except for anomalies in the dashed box.

LAHOS DATA — 3 dB DROOP CRITERION RELAXED $B\omega = 3.0$ r/s $\tau_p = 0.2$



DISCUSSION OF ANOMALIES

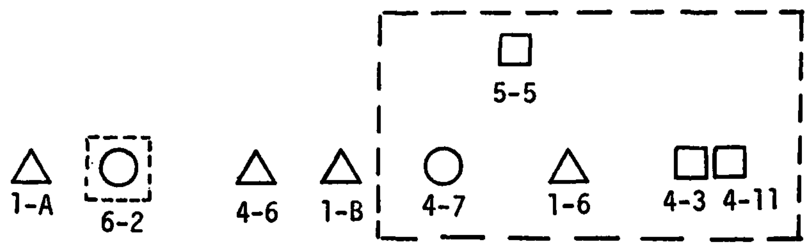
- Configuration 1-A anomalous because Safety Pilot thought rating was extreme based on performance. Not therefore considered a failure of the criterion.

- Serious violations are represented by Configs. 4-3, 4-11 and 5-5 which were rated Level 3 and fall in the Level 2 region.

- These three configurations show marked degradation in flying qualities near the ground as indicated by generally Level 1 ratings for the approach and Level 3 when the landing is included.

- Clearly, the closed-loop performance deteriorates rapidly as the pilot "tightens" control for the landing.

- Can the criterion account for these configurations which are apparently very sensitive to changes in the task?



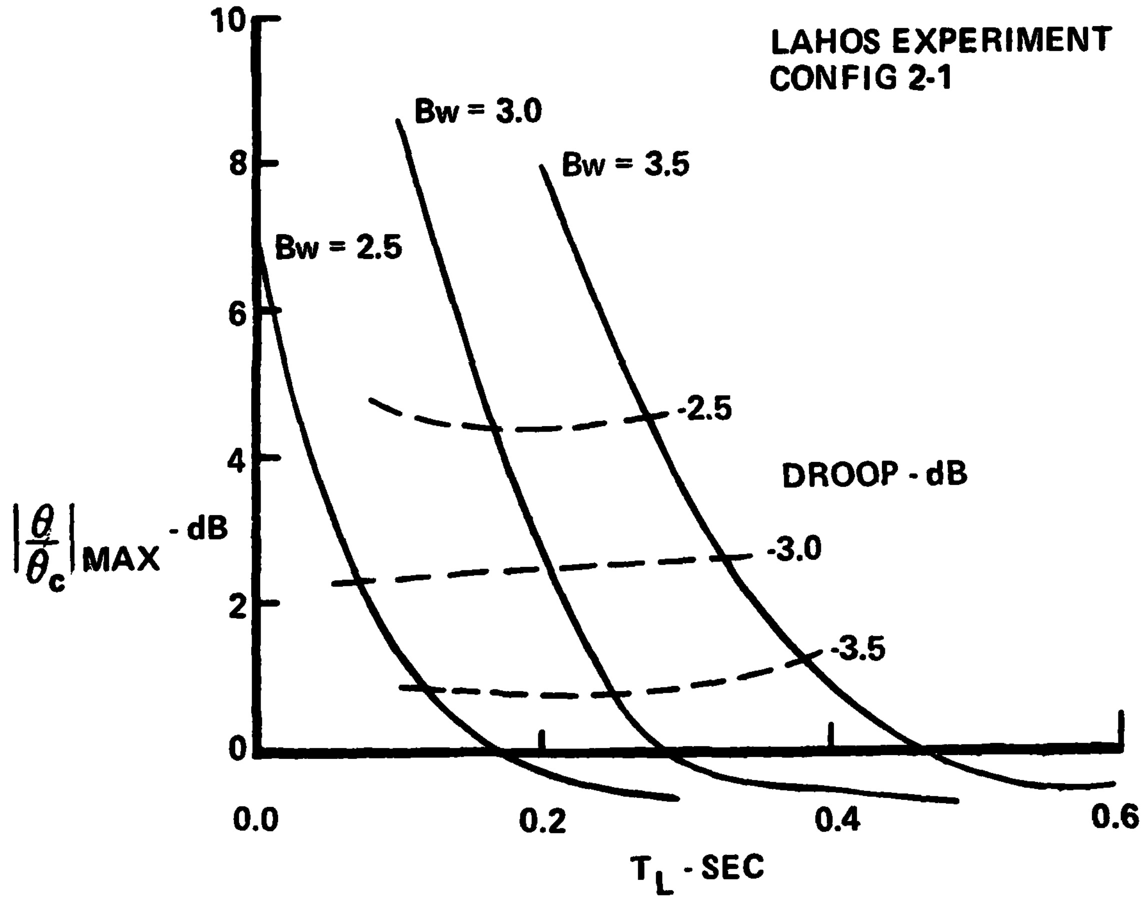
RATINGS

CONFIG.	TOTAL APPROACH	APPROACH	T.D.
1-A	6	6	4
4-6	4	1½	
1-B	5	-	
4-7	3	3	
1-C	4	-	
4-3	5 → 8	2 → 5	
4-11	8	3	
5-5	7	2	

EFFECT OF BANDWIDTH VARIATIONS ON A
"GOOD" CONFIGURATION (CONFIG 2-1)

- For a given droop, increase in bandwidth (i.e., increase in "tightness of control") can be achieved with little change in closed-loop resonance by small increases in pilot lead compensation.

VARIATION OF RESONANCE AND DROOP WITH BANDWIDTH AND LEAD COMPENSATION



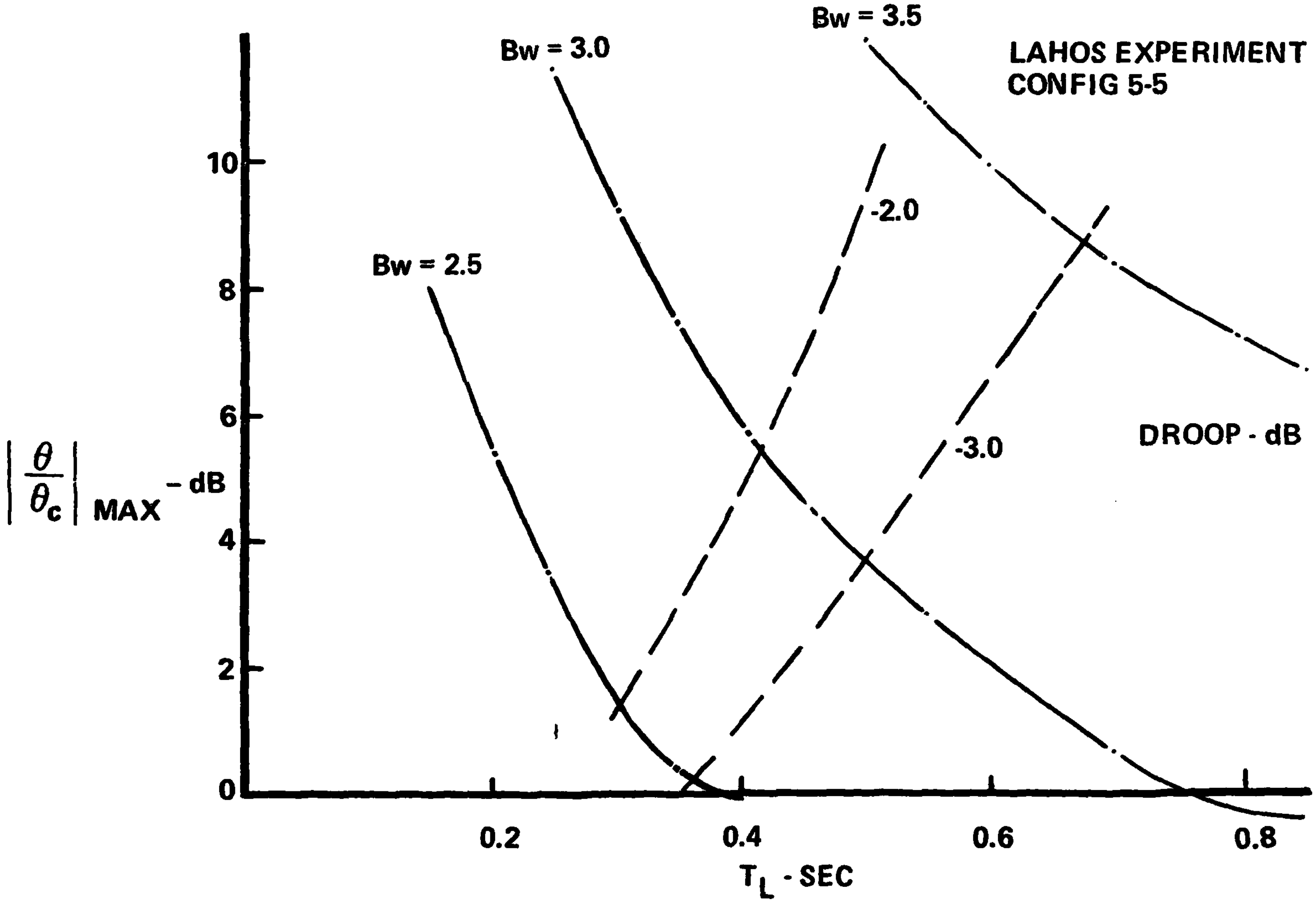
EFFECT OF BANDWIDTH VARIATIONS ON AN

ANOMALOUS CONFIGURATION (CONFIG. 5-5)

- For a given droop, increase in bandwidth can only be achieved with large increases in lead compensation and closed-loop resonance increases dramatically.

- For a reasonable limit or droop (say - 3dB), which ensures adequate low frequency closed-loop performance, the pilot cannot achieve the higher bandwidths required for the landing task without suffering the undesirable dramatic increase in closed-loop resonance.

VARIATION OF RESONANCE AND DROOP
WITH BANDWIDTH AND LEAD COMPENSATION



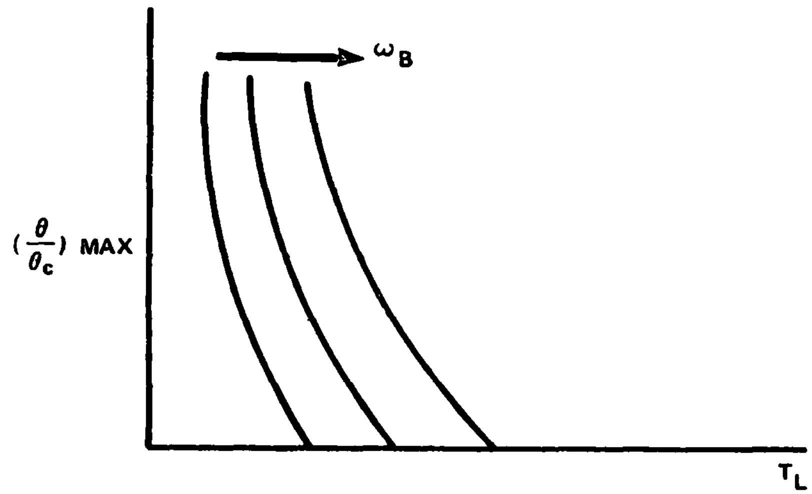
SUMMARY OF CLOSED-LOOP CONFIGURATION SENSITIVITIES

- Good configurations exhibit essentially constant closed-loop performance for a relatively wide range of bandwidths (variations in standard of performance due to task or individual pilot factors).

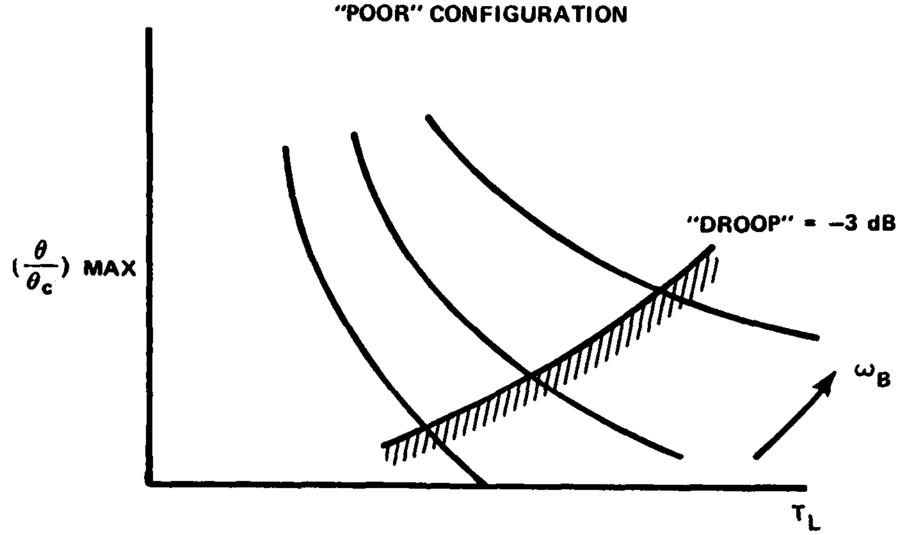
- Bad configurations exhibit large changes in closed-loop performance for small changes in bandwidth (have "flying qualities cliffs").

- Criterion needs another dimension to handle "sensitive" configurations; possible "adaptability" metrics are listed.

"GOOD" CONFIGURATION



"POOR" CONFIGURATION



POSSIBLE "ADAPTABILITY" CRITERIA

1. $\left.\dfrac{dT_L}{d\omega_B}\right|_{(\theta/\theta_c)_{MAX}} = \text{CONST}$

2. $\left.\dfrac{d\,(\theta/\theta_c)_{MAX}}{dT_L}\right|_{\omega} = \text{CONST}$

3. $\dfrac{d\,(\theta/\theta_c)_{MAX}}{d\omega_B}$

NEAL-SMITH LAHOS SUMMARY

- LANDING CRITICAL TASK
- LANDING IS HIGH BANDWIDTH TASK (FLIGHT PHASE CATEGORY A?)
- NEAL-SMITH GOOD DISCRIMINATOR (EXCEPTION: BARE AIRFRAME, LOW SHORT PERIOD DAMPING)
- POSSIBLE MODIFICATIONS
  - RELAXED DROOP REQUIREMENT
  - ADAPTABILITY
  - REDUCED PILOT DELAY

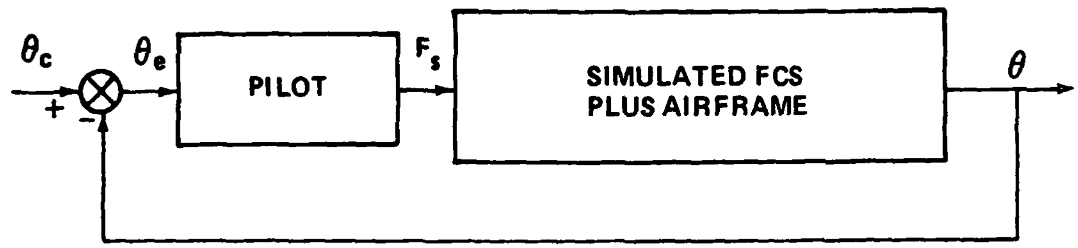
APPLICATION OF ONSTOTT'S TIME HISTORY CRITERION TO LAHOS DATA

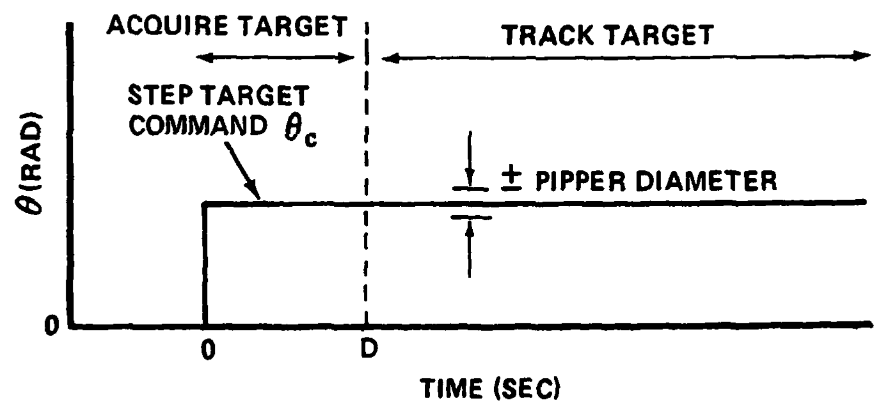
- Parameters of pilot model are adjusted in the acquisition and tracking phases to maximize time on target.

- Provided good correlation with original Neal-Smith data base.

- Appealing because aircraft with nonlinearities can be accommodated exactly.

INGREDIENTS OF STEP TARGET TRACKING CRITERION (ONSTOTT)





DEFINITION OF STEP TARGET TRACKING TASK

ACQUISITION

TIME < D, δe_I = (DELAY τ) $\left\{ K_{p_I} \left(\theta_e(t) + T_{L_I} \dot{\theta}_e(t) \right) \right\}$

TRACKING

TIME ≥ D, δe_F = (DELAY τ) $\left\{ K_{p_F} \left(\theta_e(t) + T_{L_F} \dot{\theta}_e(t) + K_{1C} \int_0^t \theta_e(s)\, ds \right) \right\}$

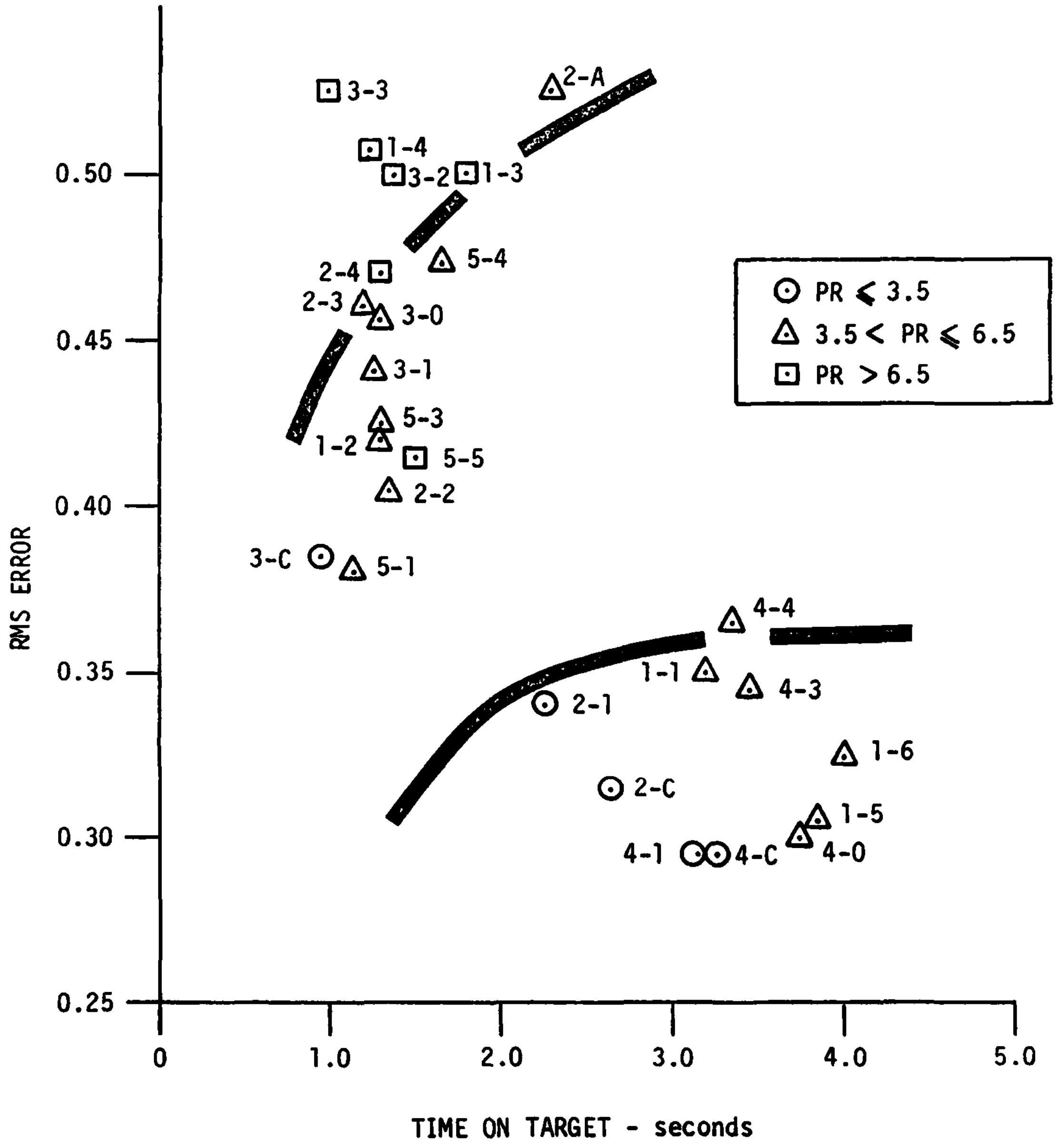
LAHOS DATA CORRELATION

- Boundaries are a function of performance measures only: time on target and RMS tracking error.

- Boundaries are based on plotted data and previous correlations with original Neal-Smith data.

- Group of anamolous ratings in Level 1 region corresponding to high times on target, e.g.: 4-0, 4-3, 1-1, 1-5, 1-6.

- Overall the correlation is reasonable but in selected cases the closed-loop time histories do not match the pilot commentary or tracking task results. These points are discussed in the next vu-graphs.

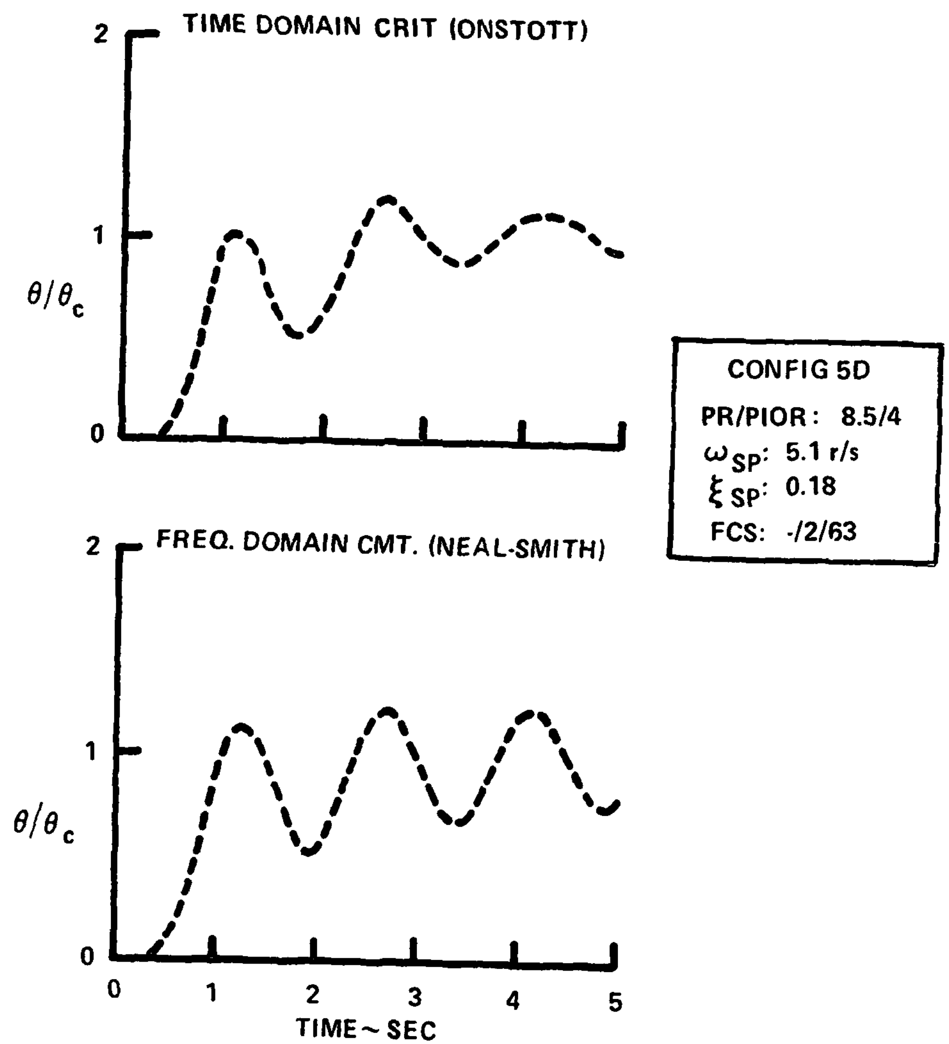


LAHOS DATA vs TIME HISTORY CRITERION

COMPARISON OF PREDICTED CLOSED-LOOP RESONANCES FOR ONSTOTT AND NEAL-SMITH CRITERIA

- Configuration 5D from original Neal-Smith data base is used for the comparison.
- Pilot rating and comments indicate a PIO-prone aircraft.
- Both criteria exhibit appropriate closed-loop responses.
- Basic aircraft low damping ratio was a factor in the PIO.

CRITERIA COMPARISON – CLOSED LOOP RESPONSE TO STEP ATTITUDE COMMAND



CLOSED-LOOP PITCH ATTITUDE RESPONSE TO A STEP ATTITUDE COMMAND

ANOTHER COMPARISON OF A PIO-PRONE CONFIGURATION

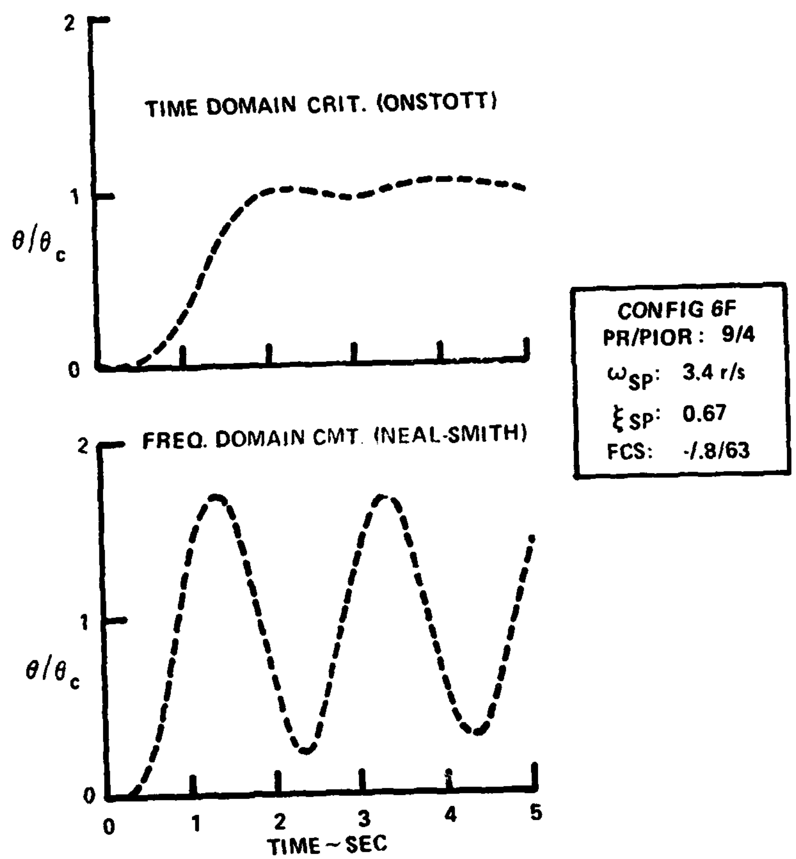
- Configuration 6F from original Neal-Smith data base is used.

- Neal-Smith predicts the correct time response for this PIO-prone configuration.

- Onstott's does not; predicts dead beat closed-loop response.

- Examination of Onstott computer program revealed an error which effectively removed the effect of pilot lead in the closed-loop transfer function.

CRITERIA COMPARISON – CLOSED LOOP RESPONSE TO STEP ATTITUDE COMMAND



CLOSED-LOOP PITCH ATTITUDE RESPONSE TO A STEP ATTITUDE COMMAND

EFFECT OF CORRECTING ERROR

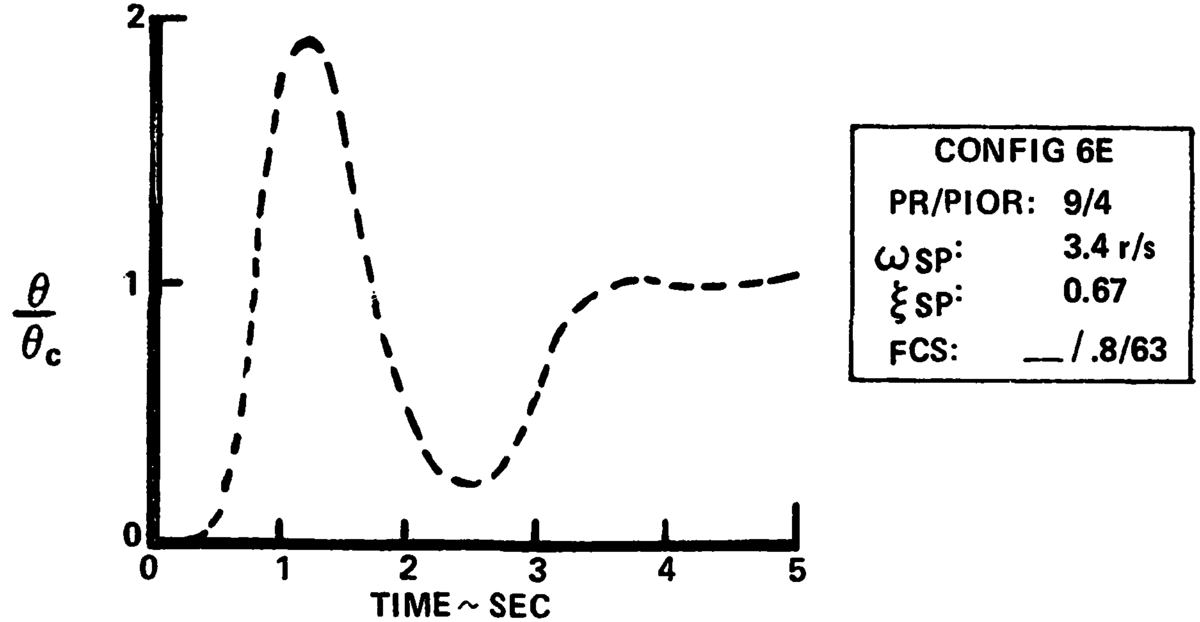
- Configuration 6F (not E as shown) is again used.

- Now the initial response is correctly oscillatory but integral term in tracking phase pilot model quickly damps the final response.

- Data must be recomputed; for certain configurations the effect of correcting the error can be significant. For example, Configuration 4-3 moves to the Level 2 boundary adjacent to Configuration 2-3 (see vu-graph 20).

- Should consider removal of integral term from tracking phase pilot model for improved correlation with observed pilot closed-loop performance.

TIME DOMAIN CRIT. (MODIFIED)



CLOSED-LOOP PITCH ATTITUDE RESPONSE TO A STEP ATTITUDE COMMAND

TIME HISTORY CRITERION SUMMARY

- o In its present form, the criterion does separate the data to a degree but the lack of correlation with observed task performance for certain types of control systems mechanizations reduces its credibility and therefore usefulness.

- o If corrected the calculated closed-loop time responses look similar to Neal-Smith results; potential of a time domain criterion is very attractive but implementation of criterion must be reviewed.

- o Absence of a workload measure in correlation parameters may be a weakness.

- o Disadvantage compared to Neal-Smith or Ralph Smith criterion is that calculation for single configuration required 5 to 10 minutes on Calspan IBM 360 with Level H compiler. Efficiency required improvement.

TIME HISTORY CRITERION SUMMARY

- HAS POTENTIAL AS CRITERION
- CLOSED LOOP LOOKS SIMILAR TO NEAL-SMITH
- BASED ONLY ON CLOSED LOOP PERFORMANCE - NO WORKLOAD MEASURE
- CALCULATION UNWIELDY - REQUIRES IMPROVEMENT

CONCLUSIONS AND RECOMMENDATIONS

- All criteria surveyed have potential but require further development.
- Landing approach, if carried to touchdown is high bandwidth task.
- Because these correlation techniques are empirical, confidence and acceptance will be achieved only through successful application to the widest possible data base.
- Should continue generation of data and correlation with criteria.

CONCLUSIONS, RECOMMENDATIONS

- NEED CRITERIA NOW !
- CLOSED LOOP TIME DOMAIN AND FREQUENCY DOMAIN CRITERIA HAVE POTENTIAL
- IN LANDING APPROACH, LAST 50 FEET CRITICAL. HIGH BANDWIDTH TASK.
- ACCEPTANCE OF CRITERIA REQUIRES VALIDATION. CONTINUE CORRELATIONS WITH EXPERIMENTAL DATA.

COMPARISON OF TWO FLYING QUALITIES DESIGN CRITERIA FOR ADVANCED FLIGHT CONTROL SYSTEMS

J. Hodgkinson

ABSTRACT

The Neal-Smith pilot-in-the-loop criterion was compared with the equivalent systems approach. A Neal-Smith bandwidth frequency was first established for augmented longitudinal dynamics in the landing approach. Then parameters from the two methods were compared.

The Neal-Smith method, though more complex, produced less information than the equivalent system parameters provide, and its answers were sensitive to choice of bandwidth frequency, for which reliable rules are not yet established.

Specific items for future work on the Neal-Smith criterion are suggested.

NOMENCLATURE

F_s	Stick Force
g	Gravitational constant, ft/sec^2
L_α	Dimensional lift curve slope parameter, /sec
n/α	Normal acceleration per angle of attack (Ref. MIL-F-8785B
S	Laplace parameter
$1/T_{\theta_2}$	Actual numerator root in short period pitch rate transfer function ($1/T_{\theta_2} \approx L_\alpha$)
V_T	True speed, ft/sec
$\dot{\theta}$	Pitch rate
$\left\lvert \frac{\theta}{\theta_c} \right\rvert_{max}$	Magnitude of resonant peak in the θ/θ_c Bode amplitude plot (dB).
ζ_e	Equivalent longitudinal short period damping ratio
ω_e	Equivalent longitudinal short period frequency, radians/sec
τ_e	Equivalent time delay, seconds
OC	Phase angle of the pilot compensation of the bandwidth frequency, degrees

INTRODUCTION

THE NEAL-SMITH CRITERION - The Neal-Smith criterion is an analytical procedure to explain the flying qualities of fighter aircraft with augmented short period pitch dynamics. Developed by Neal and Smith (Reference 1), it is based on fundamental studies of manual control by Systems Technology Incorporated (STI) (for example, Reference 2). The pilot is assumed to have a fixed delay, and variable gain, and lead/lag time constants (Figure 1). These are varied so that the closed loop dynamics exhibit a low frequency droop of 3 dB and the bandwidth frequency defined in Figure 2. The pilot lead or lag phase angle at the bandwidth frequency is then plotted against the closed loop resonance and compared with the boundaries of Figure 3. The physical interpretation of the regions of the Neal-Smith plane is indicated in Figure 4.

Figure 3 also shows a modified upper boundary proposed by Rickard (Reference 3). The modification was proposed because Neal and Smith's original calculations were performed by hand (Reference 1). Subsequently, Mayhew wrote a computer program which calculated the needed parameters (Reference 4). Later, Rickard improved the efficiency of Mayhew's program and used it to re-calculate the parameters of the entire data set of Reference 1. This resulted in somewhat different closed loop resonances, and hence boundaries. Rickard's version of the computer program was used for this present study.

Evidently, the judgments and assumptions which have been arbitrarily set in the program affect the answers. For example, the choice of 3dB is arbitrary, as is the pilot delay of 0.3 sec. The first order lead-lag pilot form is not necessarily appropriate for some aircraft dynamics. Generally, and in most of the work described here, these parameters are fixed. However, bandwidth frequency must be chosen to match the pilot's task. Bandwidths of 3.0 and 3.5 rad/sec were used by Neal and Smith for up-and-away tasks in Reference 1. A value of 1.2 rad/sec was recommended for landing approach in Reference 5, and was also used by Rickard in Reference 3.

THE EQUIVALENT SYSTEMS APPROACH - An equivalent system is a low order mathematical model which matches the high order model response. Equivalent parameters have been widely used for comparison and correlation of the flying qualities of high order dynamics of CTOL and V/STOL aircraft. Where applicable, the equivalent parameters are compared with suitably modified modal requirements, such as those in MIL-F-8785B(ASG), giving reasonable prediction of flying qualities, as discussed by A'Harrah et al. in Reference 6.

For the present study, the equivalents were obtained using a computer program to match the high order frequency response in the range .1 to 10 radians/sec, using the equation

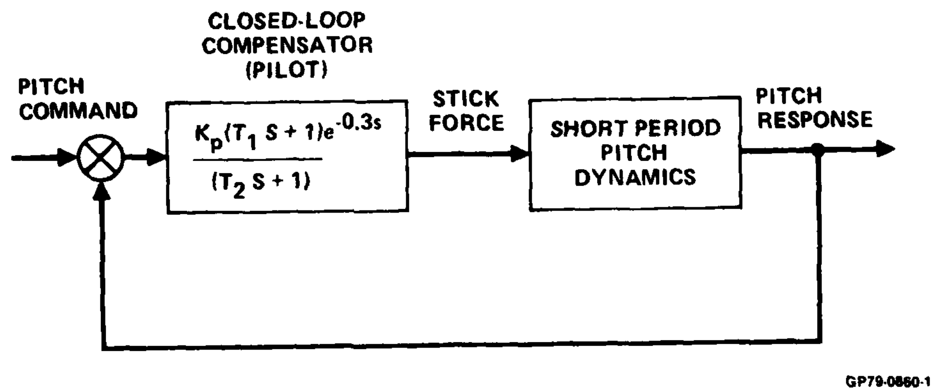


FIGURE 1
CLOSED-LOOP RESPONSE MODEL IN NEAL-SMITH CRITERION

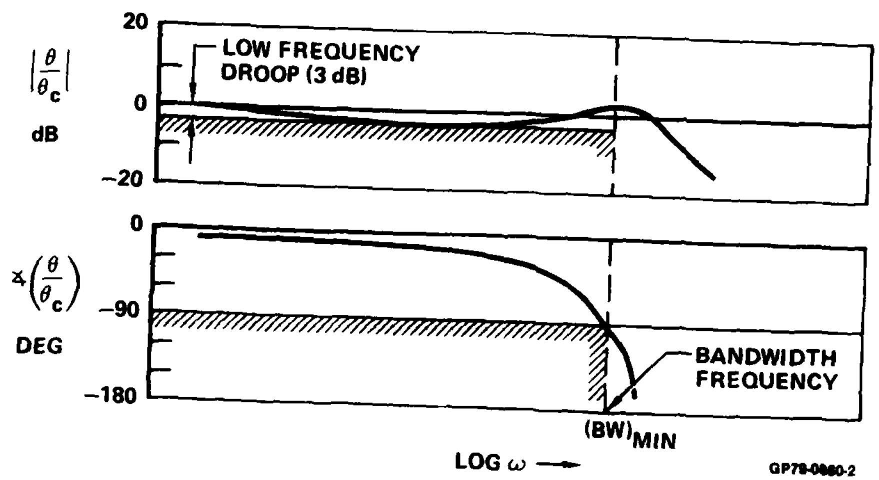


FIGURE 2
CLOSED LOOP RESPONSE CRITERIA IN NEAL-SMITH CRITERION

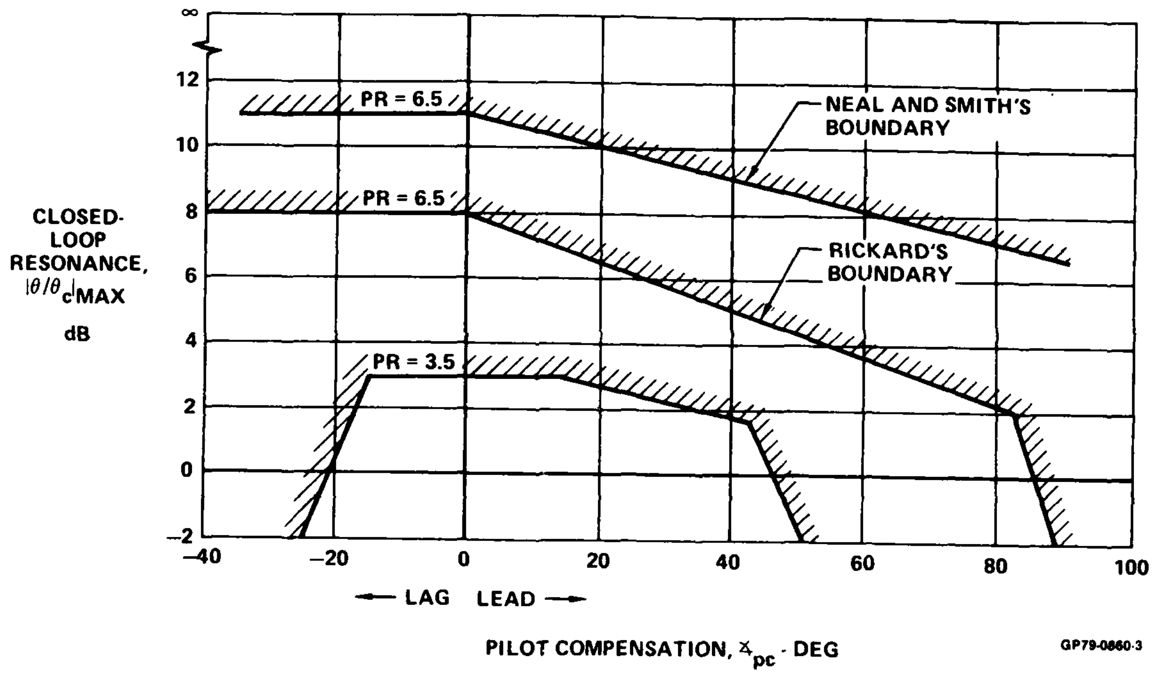


FIGURE 3
NEAL-SMITH BOUNDARIES WITH RICKARD'S CORRECTION TO UPPER BOUNDARY

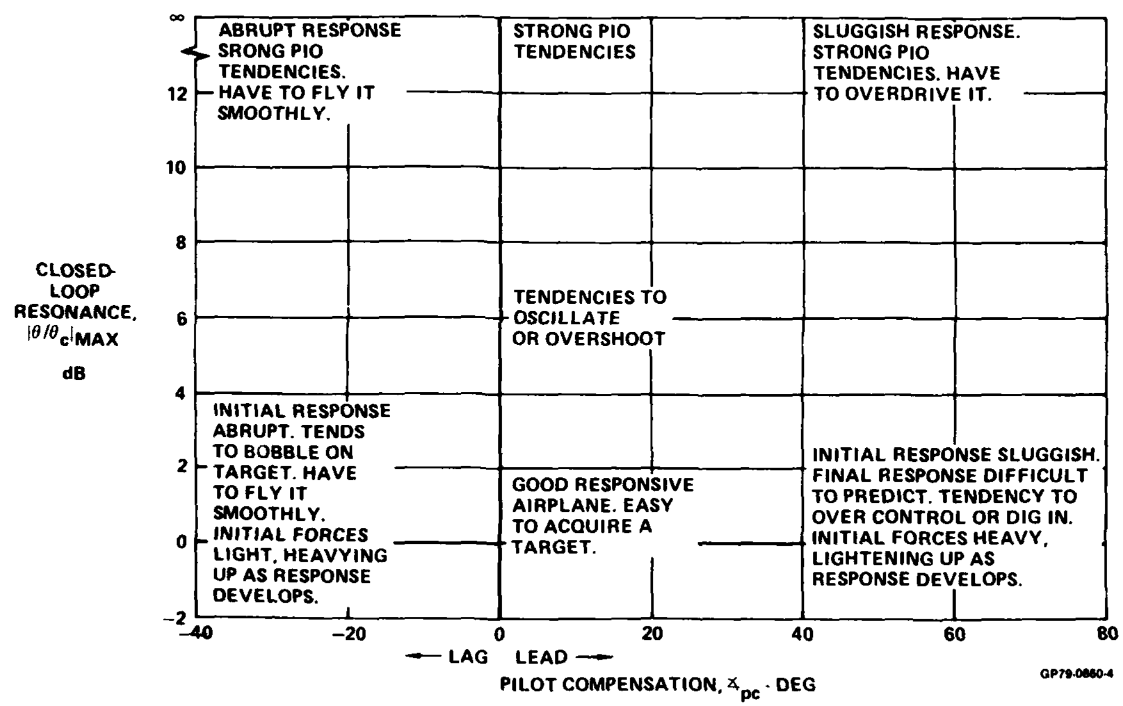


FIGURE 4
PILOT COMMENT DATA AS A FUNCTION OF NEAL-SMITH CLOSED-LOOP PARAMETERS

$$\frac{\dot{\theta}}{F_S} = \frac{K(T_{\theta_2} S + 1)e^{-\tau_e S}}{\frac{S^2}{\omega_e^2} + \frac{2\zeta_e}{\omega_e} S + 1} \quad (1)$$

where K, τ_e, ζ_e and ω_e were the search variables. $1/T_{\theta_2}$ was retained at the true value appropriate for the airframe (approximately L_α) for simplification.

Example matches of varying quality appear in Figure 5. Although these are arbitrarily referred to as good, fair and poor, experimental data from a recent NT-33 program (Reference 7) indicate that these mismatches are negligible to pilots. The equivalent parameters are therefore used herein without regard to quality of match.

OBJECTIVES - The first objective was to find the bandwidth frequency in the Neal-Smith method which would produce the best correlation with a new set of landing approach high order system (LAHOS) data, Reference 8. Like Neal and Smith's up-and-away experiment, LAHOS evaluated a variety of short period longitudinal dynamics, with lead and lag elements added to produce various types of high order effects.

The second objective was to compare the Neal-Smith method with the equivalent system method.

It is stressed that this report refers only to short period pitch dynamics, the only problem for which the Neal-Smith criterion has been developed. The wider applications of equivalent systems to other axes and modes are not examined.

DETERMINATION OF BANDWIDTH FREQUENCY FOR LANDING APPROACH (LAHOS) DATA - Figure 6 indicates typical variations of the closed loop resonances and pilot compensation as bandwidth is changed. As bandwidth is increased, more lead compensation is required, and ultimately closed loop resonance increases. Changing bandwidths from 1.5 rad/sec to 4.0 rad/sec can change the predicted level of flying qualities from Level 1 to Level 3.

Chalk, et al. in Reference 5 suggested that a bandwidth of 1.2 rad/sec might be appropriate for the landing approach, based on an extrapolation of Neal and Smith's original results. It is evident from Figures 6 and 7 that this bandwidth, with force commands and a pilot delay of 0.3 seconds, is not high enough. Figure 8, obtained following some trial and error, shows that 2.5 rad/second is more appropriate. The original boundaries exhibit somewhat better correlation than the corrected (Rickard's) version.

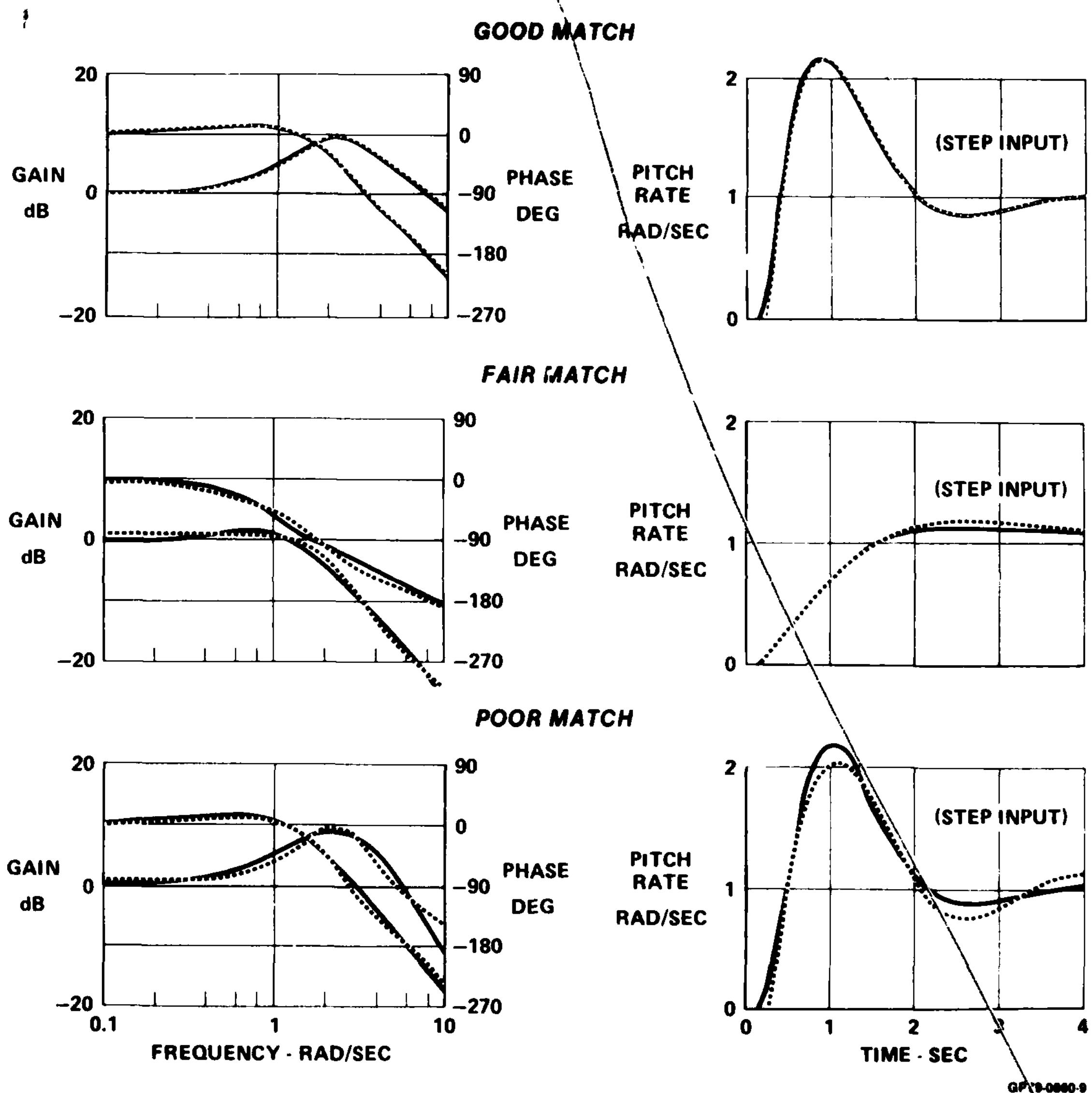


FIGURE 5
EXAMPLES OF GOOD, FAIR AND POOR LONGITUDINAL SHORT PERIOD PITCH RATE EQUIVALENT SYSTEMS

Notes:

1. Position commands, pilot delay = 0.2 sec
2. Various LAHOS configurations (Reference 8)
3. PR = pilot rating

Symbol	Bandwidth (rad/sec)
○	1.5
□	2.0
△	2.5
◇	3.0
◿	3.5
◖	4.0

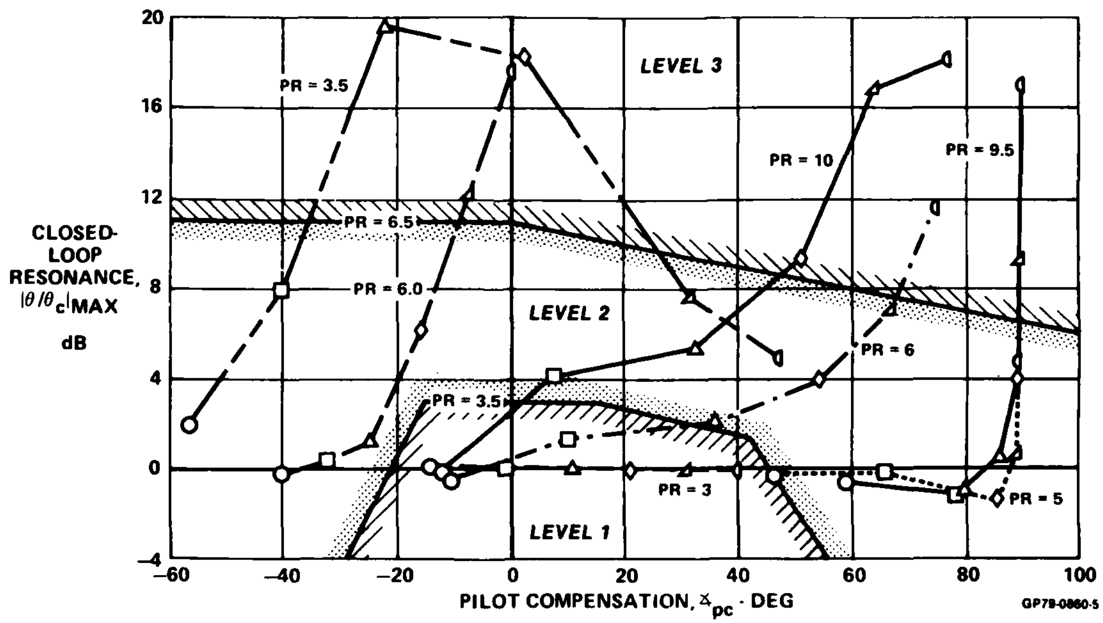


FIGURE 6
DEPENDENCE OF NEAL-SMITH PARAMETERS ON BANDWIDTH FREQUENCY
LAHOS Data

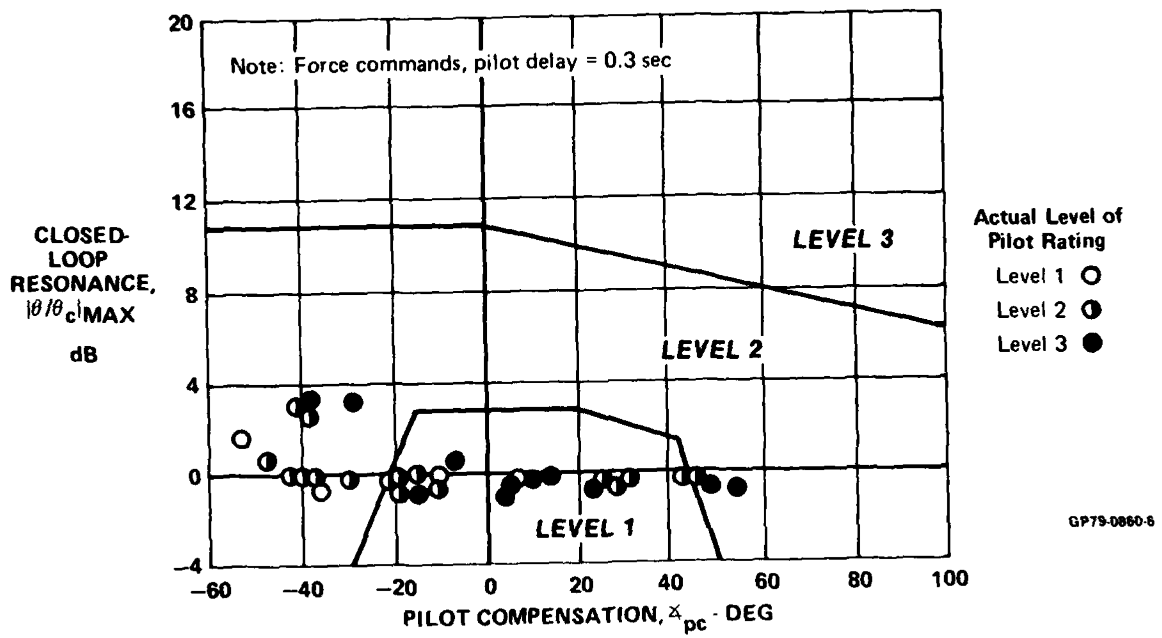


FIGURE 7
POOR CORRELATION WITH NEAL-SMITH BOUNDARIES USING BANDWIDTH FREQUENCY = 1.2 RAD/SEC
LAHOS Data

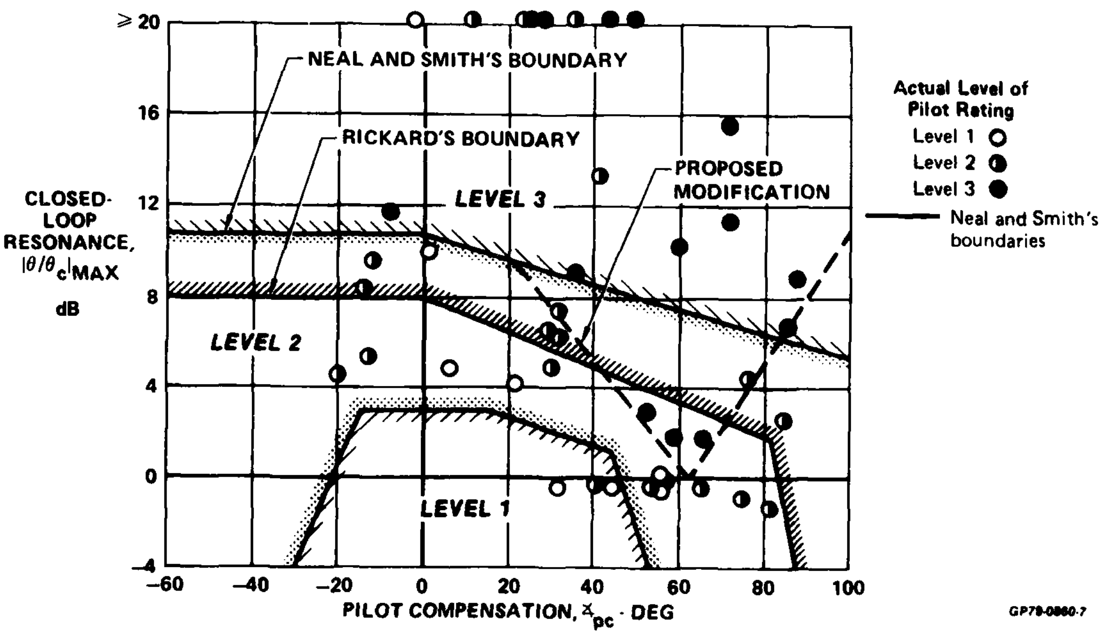


FIGURE 8
ADEQUATE CORRELATION WITH MODIFIED NEAL-SMITH BOUNDARIES USING 2.5 RAD/SEC FOR BANDWIDTH FREQUENCY
LAHOS Data

Even with this optimum bandwidth of 2.5 rad/sec, Figure 8 shows poor correlation for a group of configurations at the top of the plot. In fact, it was necessary to ignore the feel system and actuator lags in order to obtain these results from the computer program. Including these high frequency lags caused error messages with no output parameters.

It is possible that a different bandwidth would produce better correlation for these configurations. This implies that bandwidth should be a function of aircraft parameters, because all these points have low equivalent short period damping. However, the criterion has no provision for this at present. These configurations were not included in the further discussions here.

There is also a region in the plane in which Level 3 and Level 1 points are closely adjacent. This is around 40 to 60° lead compensation at small resonances. The Level 3 points in this region can be better correlated with modified boundaries, as indicated in the figure. These modified boundaries reflect not only the rating data (the downturn in the boundary with lead compensation increase) but also the artificial constraint of 90° pilot lead compensation (the upturn in the boundary as lead compensation approaches 90°).

Figure 9 plots the parameters $1/T_{\theta 2}$, V_T, and n/α against the various bandwidth frequencies which have been used for correlating NT-33 data. It is not known, however, which of these parameters (if any) would underlie an actual pilot's choice of bandwidth in a given flying qualities task.

COMPARISON WITH EQUIVALENT SYSTEMS - The LAHOS experimental design allows examination of Neal-Smith parameters for groups of configurations with the same ζ_e and ω_e, and various τ_e. These are summarized in Figure 10, which is the starting point for the more detailed comparisons which follow.

Equivalent Short Period Frequency and Pilot Lead Compensation - In this comparison, the equivalent frequencies were obtained with $1/T_{\theta 2}$ fixed at the basic aircraft value in the matching process.

It would be expected that an inverse relationship exists between frequency and lead compensation. For example, a low frequency would require a large lead compensation, and Figure 10 confirms this.

Figure 11 compares equivalent frequency and pilot lead compensation for all the LAHOS data. By far most of the pilot compensation is explained by the simple expression

$$\measuredangle PC = 114.2 - 33.8\ \omega_e \qquad (2)$$

Figure 12 shows the Neal-Smith data obtained using different bandwidths. The frequency and compensation values are similar

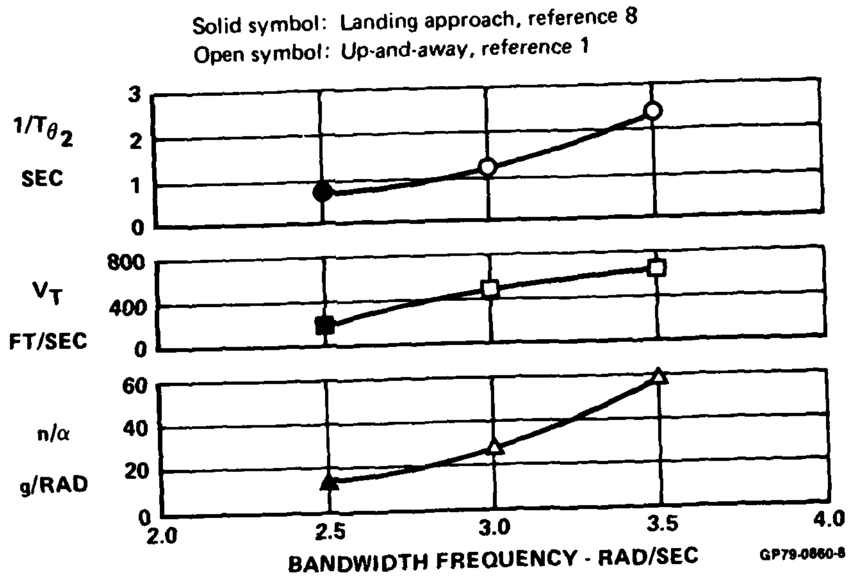


FIGURE 9
BEST-CORRELATING BANDWIDTH FREQUENCY AS A FUNCTION OF THREE MEASURES OF FLIGHT CONDITION

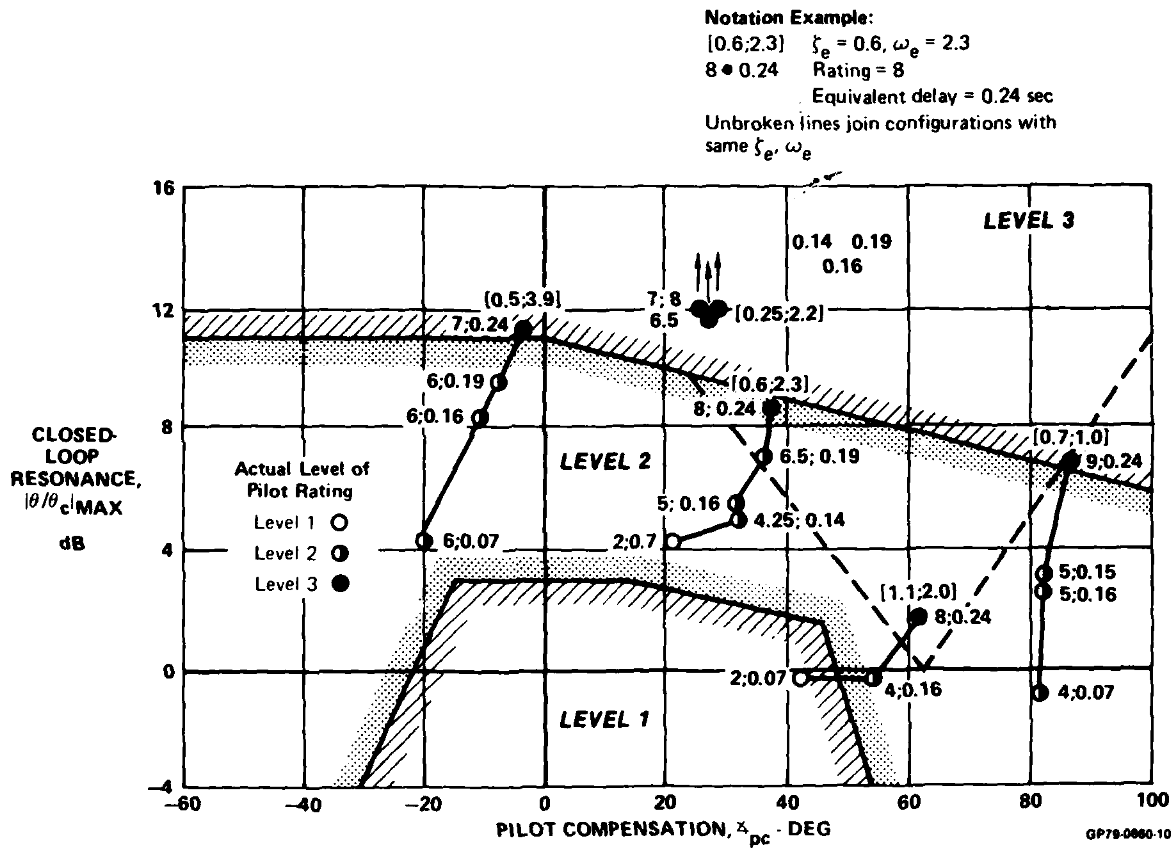


FIGURE 10
COMPARISON OF LAHOS EQUIVALENT SYSTEMS WITH NEAL-SMITH BOUNDARIES

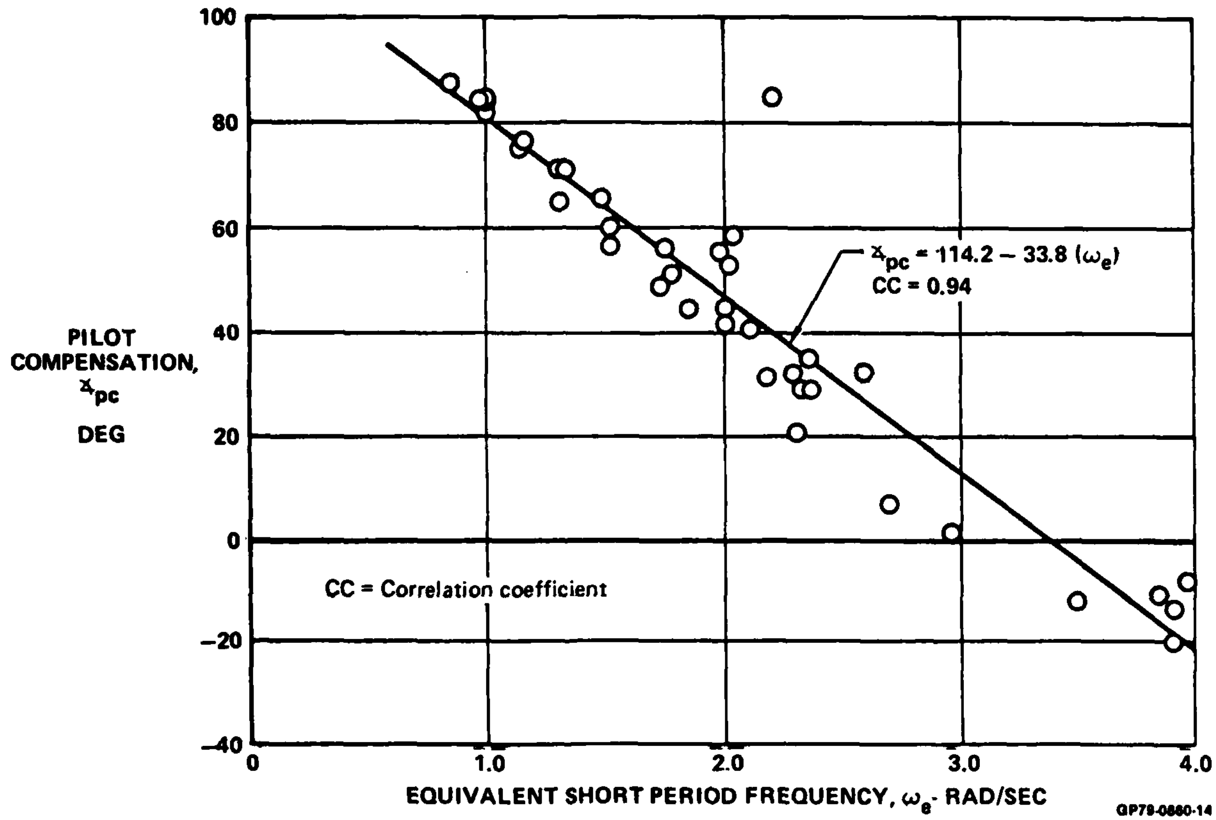


FIGURE 11
COMPARISON OF PILOT COMPENSATION vs EQUIVALENT SHORT PERIOD FREQUENCY
LAHOS Data

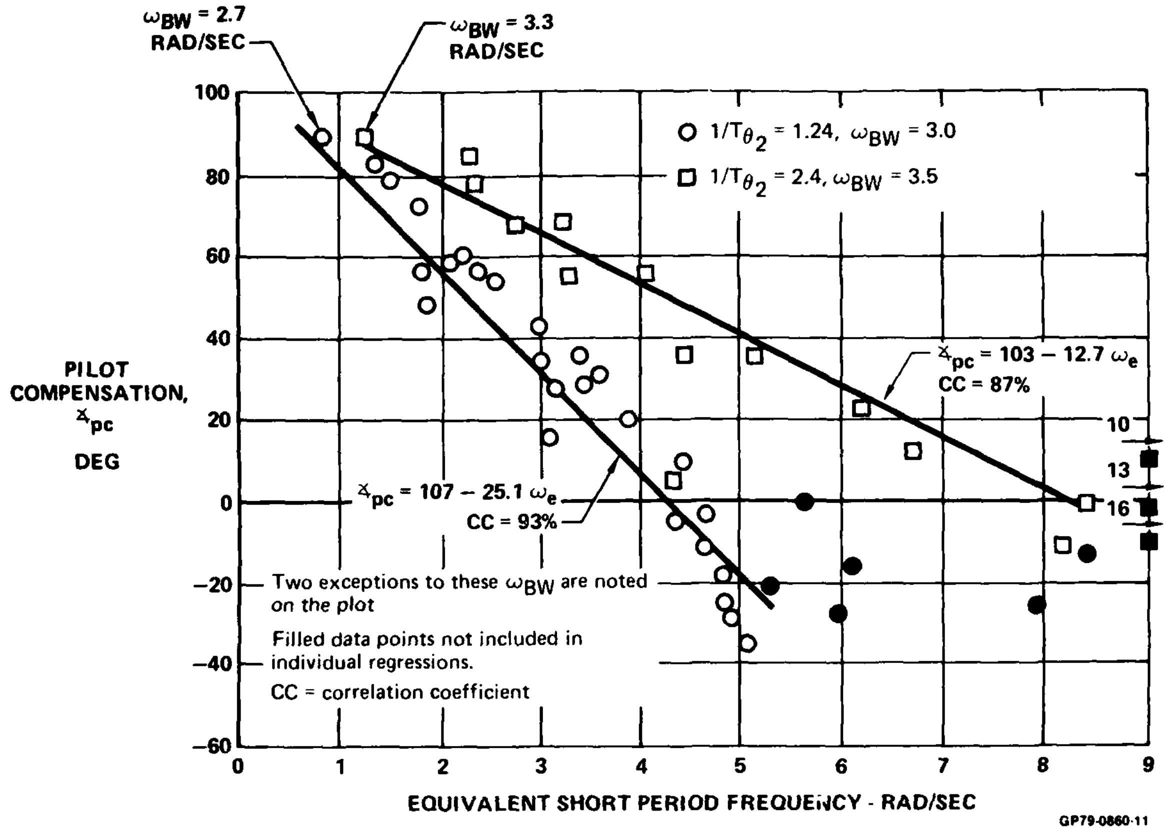


FIGURE 12
PILOT COMPENSATION vs EQUIVALENT SHORT PERIOD FREQUENCY
Neal-Smith Data

for the three different bandwidths near the ($\omega_e = 0$, $\measuredangle P_C = +90°$) point, because extremely slow dynamics require maximum lead compensation to attain any closed loop bandwidth. The Neal-Smith and LAHOS data radiate linearly from this point, with different slopes for different bandwidths and little scatter.

The slopes are an inverse function of the airframe parameter $1/T_{\theta_2}$, and the expression

$$\measuredangle P_C = 95 - 21\ T_{\theta_2}\ \omega_e \tag{3}$$

produced a correlation coefficient of 85% for the LAHOS and Neal-Smith data combined. An expression which used the MIL-F-8785B parameter $\omega_e^2/n/\alpha$,

$$\measuredangle P_C = 61 - 25\ \omega_e^2/n/\alpha \tag{4}$$

produced a correlation coefficient of 73%.

<u>Equivalent Short Period Damping Ratio, Time Delay, and Closed Loop Resonance</u> - Figure 10 indicates an inverse relationship between closed loop resonance and equivalent damping for the LAHOS data. Poorly damped configurations produce large values of resonance, as would be anticipated. It is clear from Figure 10 and from Figure 13 and 14, however, that damping is not the sole influence; equivalent delay is partly responsible.

A simple expression accounting for 80.5% of the variation in closed loop resonance for the LAHOS and Neal-Smith data combined, was obtained using stepwise multiple linear regression;

$$\left|\frac{\theta}{\theta_c}\right|_{max} = -\ 6.3 + 45.0\tau_e + \frac{4.3}{\zeta_e} \tag{5}$$

The regression indicated that resonance was more strongly correlated with delay than with the inverse of damping.

STI has proposed a high gain asymptote parameter which relates closed loop tracking instabilities to the difference between $1/T_{\theta_2}$ and $2\zeta_e\omega_e$. The ratio of these parameters was found to be highly correlated with pilot rating in References 9 and 10. Adding this ratio to the prediction of closed-loop resonance produced a correlation coefficient of 85%, using the following equation:

$$\left|\frac{\theta}{\theta_c}\right|_{max} = -\ 7.6 + 9.2\ \frac{(1/T_{\theta_2})}{2\zeta_e\omega_e} + 41.1\ \tau_e + \frac{3.4}{\zeta_e} \tag{6}$$

In this regression, the high gain asymptote parameter showed the most correlation with resonance.

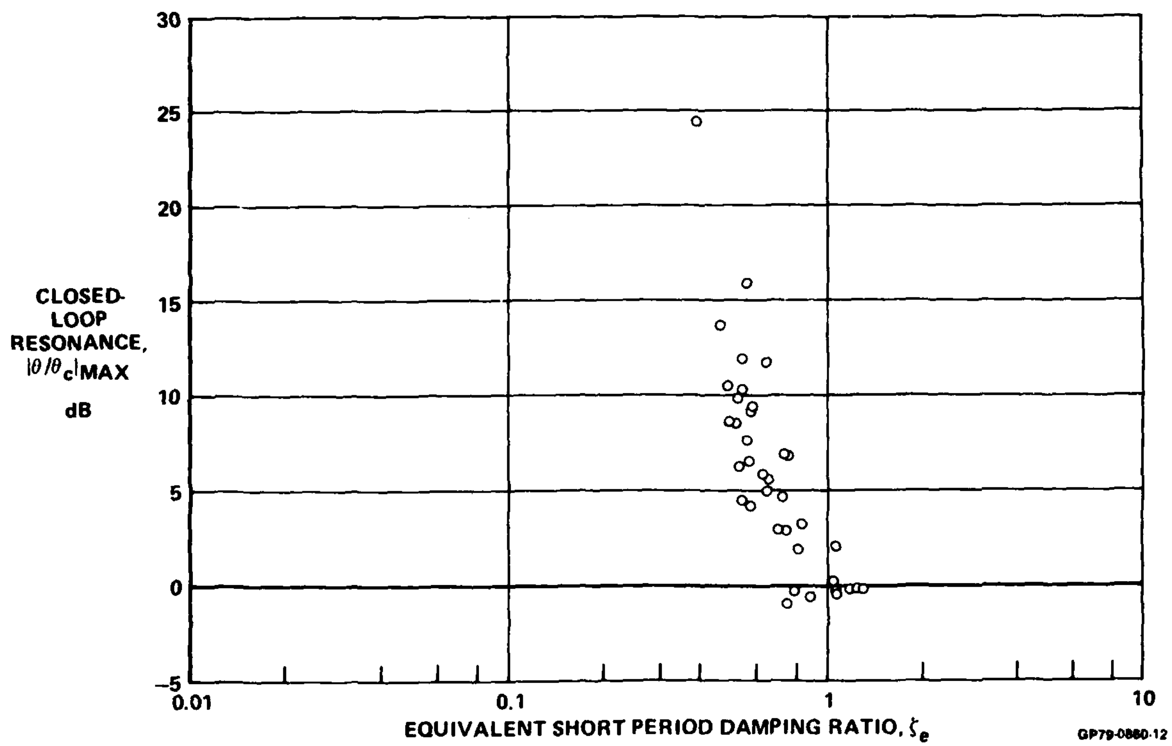


FIGURE 13
COMPARISON OF CLOSED-LOOP RESONANCE vs EQUIVALENT SHORT PERIOD DAMPING RATIO
LAHOS Data

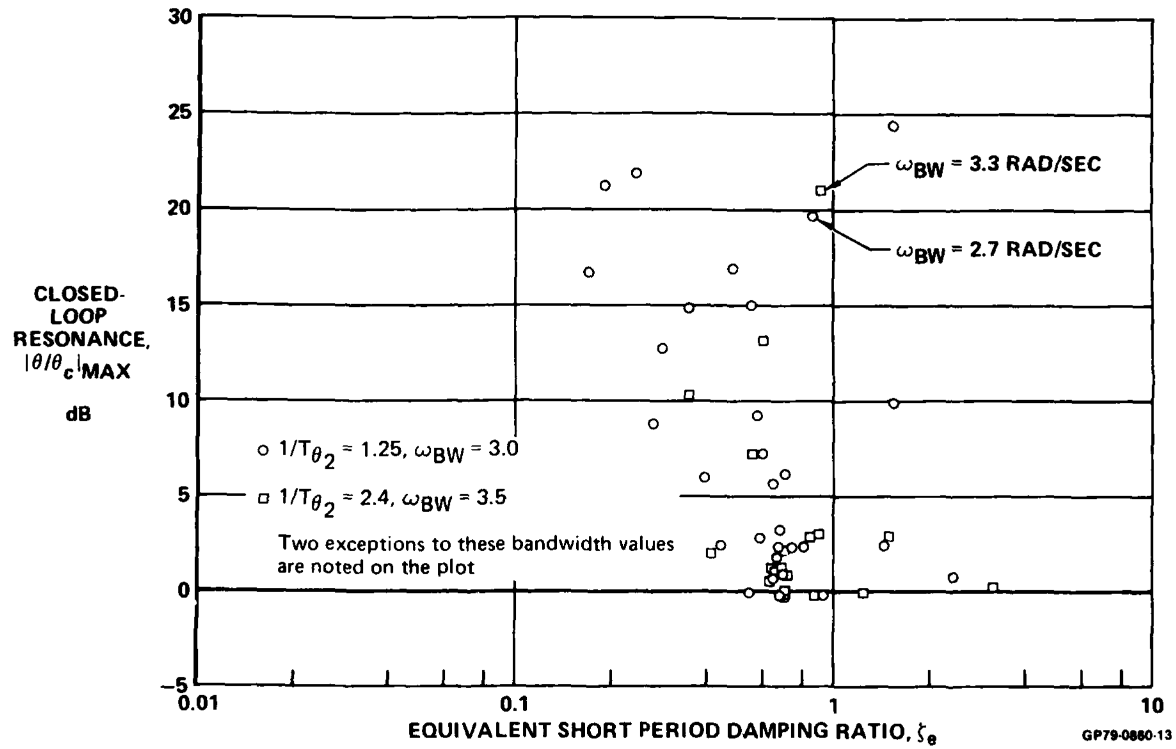


FIGURE 14
COMPARISON OF CLOSED-LOOP RESONANCE vs EQUIVALENT SHORT PERIOD DAMPING RATIO
Neal-Smith Data

SUMMARY AND CONCLUSIONS

Both the Neal-Smith criterion and the longitudinal short period equivalent systems produce results which are physically consistent with closed-loop and open-loop viewpoints, respectively. A primary accomplishment of the Neal-Smith approach is that it predicts the unfavorable effects of high-frequency lags (equivalent delays). Work with equivalent systems has shown this is a prerequisite for criteria aimed at highly augmented dynamics.

However, the Neal-Smith technique has some areas in need of further work before it becomes a reliable design criterion:

(1) Establishment of rules for bandwidth choice for new tasks, dynamic axes, aircraft types, flight conditions, etc. For example, the criterion has been used with three different bandwidths (3.0, 3.5, 2.5) and three sets of boundaries (the original Neal-Smith, Rickard's, and the modified boundaries proposed in this present study) to explain variations in longitudinal short period attitude dynamics of the NT-33 aircraft.

(2) Re-examination of the region around $\measuredangle P_C = 60°$, where widely differing configurations exhibit little change in the Neal-Smith parameters.

(3) Modification of both the criterion and the computer program to account for configurations with low equivalent damping values.

(4) Extension to phugoid and flight path dynamics for longitudinal landing problems in addition to those encountered in the LAHOS experiment.

(5) Thorough documentation of a suitable computer program.

It is recognized that more simulation data are needed to address some of these items.

The Neal-Smith technique reduces longitudinal short-period flying qualities dynamics to a two-dimensional problem rather than the four-dimensional problem resulting from equivalent systems. Although this can be advantageous for visibility, the designer actually works with the four dimensions of ζ_e, ω_e, $1/T_{\theta_2}$, and τ_e. As is argued in Reference 11, each of these parameters is related to familiar airframe and flight control design parameters. The designer is not guided by the closed-loop resonance parameter into deciding between, for example, changing pitch rate feedback gain or the digital computation interval. Equivalent damping and time delay values are needed to provide this guidance. Therefore, the Neal-Smith technique complicates the design process, as compared with a more direct equivalent systems approach.

A closed-loop approach is usually adopted because of flying qualities phenomena which cannot be explained based on open-loop dynamics alone. However, based on the comparisons shown in this paper, the Neal-Smith technique offers no information beyond equivalent system parameters. The qualitative interpretations of the Neal-Smith plane (Figure 4) are typical of comments due to corresponding equivalent parameters in the simple equations (2)-(6) shown above.

In spite of the above remarks, the Neal-Smith approach should not be abandoned in favor of the equivalent systems approach.

In the context of high-speed computers which calculate flying qualities parameters with considerable rapidity, it is unproductive to search out the single appropriate flying qualities design criterion. All worthwhile analytical and experimental techniques should be used. Prudent design demands this approach, and also demands that skilled engineers assign weighting factors or confidence levels to various criteria based on experience with the criteria and on their stage of development. It is hoped that this present study will aid in assigning these weights, as well as in suggesting areas for future study.

ACKNOWLEDGEMENTS

This paper summarizes work performed as part of the ongoing MCAIR Independent Research and Development on Flight Dynamics and Flying Qualities. Those who have contributed in the past approximately two years include:

Randall Bailey
James E. Buckley
John R. Dykman
Keith J. Glass
Karl A. Johnston

David J. Moorhouse, AFFDL/FGC provided information which was most helpful, and Rogers E. Smith of CALSPAN provided valuable help and suggestions. William W. Rickard of Douglas Aircraft provided unpublished work from the Douglas Independent Research and Development.

REFERENCES

1. Neal, T.P., and Smith, R.E., "An In-Flight Investigation to Develop Control System Design Criteria for Fighter Airplanes", AFFDL-TR-70-74, December 1970.

2. McRuer, D., et al., "Human Pilot Dynamics in Compensatory Systems", AFFDL-TR-65-15, July 1965.

3. Rickard, W.W., "Longitudinal Flying Qualities in the Landing Approach", Douglas Paper 6496, 12th Annual Conference on Manual Control, 25-27 May 1976.

4. Mayhew, D.R., "A Digital Computer Program for the Calculation of Parameters Necessary to Satisfy the Closed-Loop Criteria of T.P. Neal", AFFDL/FGC TM 73-110, August 1973.

5. Chalk, C.R., et al., "Revisions to MIL-F-8785B(ASG) Proposed by Cornell Aeronautical Laboratory Under Contract F33615-71-C-1254", AFFDL-TR-72-41, April 1973.

6. A'Harrah, R.C., et al., "Are Today's Specifications Appropriate for Tomorrow's Airplanes?" AGARD Flight Mechanics Symposium on Stability and Control 25-28 September 1978.

7. Hodgkinson, J., and Johnston, K.A., "Initial Results of an Inflight Simulation of Augmented Dynamics in Fighter Approach and Landing" MCAIR Paper 79-019, AIAA Guidance and Control Conference, Boulder, Colorado, 6-8 August 1979.

8. Smith, R.E., "Effects of Control System Dynamics on Fighter Approach and Landing Longitudinal Flying Qualities (Vol. I)", AFFDL-TR-78-122, March 1978.

9. Hodgkinson, J., LaManna, W.J., and Heyde, J.L., "Handling Qualities Analysis of the Aircraft with Stability and Control Augmentation Systems - A Fundamental Approach", J. RAeS, February 1976.

10. Johnston, K.A., and Hodgkinson, J., "Flying Qualities Analysis of an In-Flight Simulation of High Order Control System Effects on Fighter Aircraft Approach and Landing", MDC Report A5596, December 1978.

11. Hodgkinson, J., "Equivalent Systems Approach for Flying Qualities Specification", MCAIR Paper 79-017, SAE Aerospace Control and Guidance Systems Committee Meeting, Denver, Colorado, 7-9 March 1979.

QUESTIONS/ANSWERS

R. C. RADFORD: Calspan Corporation

- I disagree with your second conclusion that the equivalent systems criterion is superior to other techniques such as Neal-Smith. Your assumption that parameters such as equivalent short period frequency and damping aid the designer is difficult to understand. For instance, taking your example of a longitudinal flight control system which is 54th order, how would the knowledge that the equivalent short period frequency is too low tell the designer what to change, prefilter or feedback gains or shaping networks, any more readily than Neal-Smith. Would you comment please.

- The designer starts with a basic airplane which posseses certain flying qualities deficiencies - for example, low frequency. In this case, he designs a flight control system which produces higher equivalent frequency. He therefore knows by definition which features affect equivalent frequency. The development process might subsequently lead to a complex system, however the designer can never lose sight of the basic closed- and open-loop interrelationships. A designer who cannot make a decision between prefilter or feedback gains or shaping networks merely because his system is 54th order, has lost sight of his system and is no longer its designer.

  This might be an appropriate place to acknowledge that a 54th order system (mentioned in the verbal presentation as an example of an existing system's complexity) requires more careful checking than a 4th order system, and that the USAF/Calspan NT-33 has become an invaluable development tool for this purpose. We are also very interested in the NT-33 simulation of various flight control systems in AFFDL-TR-74-9, which when taken together with STI's cautions on 'complexity traps' (NASA CR-2500) and our own work on equivalent delays at MCAIR, suggests that 54th order systems should be avoided if possible.

C. R. CHALK: Calspan Corporation

- Have you looked at configurations with unstable real roots? You may have to look at a lower frequency range to cover this problem, i.e., the equivalent system mismatch lower frequency should be less than .1 radians/second. Also, what was the purpose of the regression equations? Were they intended to be new flying qualities criteria?

- We have not examined unstable real roots, because these are usually due to augmentation failures which result in low order systems. We routinely lower the match frequency an additional decade or so to establish equivalent phugoid or spiral roots, however. The appropriate order of equivalent should then be chosen (eg 2nd/4th). An AIAA paper (AIAA Atmospheric Flight Mechanics Conference, Hollywood, Florida, 8-10 August 1977) describes our approach to phugoid determination. (See also MCAIR paper 77-016).

The regression equations were not intended as new flying qualities criteria. They are intended to show that the Neal-Smith parameters are restatements of old flying qualities criteria. MIL-F-8785 is a more general and better substantiated way of using equivalent system parameters at present.

R. J. Woodcock: AFFDL

- Matching responses down to .01 rad/sec to define equivalent system parameters would seem to involve the phugoid mode as well as the short period.

- As mentioned above, we have determined equivalent phugoid dynamics by increasing the system order and expanding the frequency range. Interpretation of existing phugoid (or spiral) requirements using equivalent phugoids would be preferable to a 'dominant root' approach.

Comparison of the LAHOS Data with the
Mayhew Equivalent System Boundaries

David J. Moorhouse
AF Flight Dynamics Laboratory

INTRODUCTION

MIL-F-8785B, "Military Specification - Flying Qualities of Piloted Airplanes", contains requirements for short-term pitch control. These requirements take the form of maximum and minimum values of short-period frequency (as functions of normal acceleration per unit angle of attack, n_α), plus maximum and minimum values of short-period damping ratio, assuming a classical short-period mode is present. A discussion as to whether the numerator time constant, $1/T_{\theta_2}$, or n_α is the correct parameter is acknowledged (see Reference 1), but will not be pursued here. The criteria in the specification are thus open-loop response parameters, although the data correlation was based on considerations of pilot control requirements. A criterion incorporating more direct pilot-in-the-loop considerations was proposed by Neal and Smith[(2)]. Their final result was in the form of boundaries on a plot of closed-loop resonance vs required pilot lead/lag compensation, on the assumption that the pilot opinion of flying qualities (for pitch maneuvering task) is a function only of closed-loop amplitude and phase characteristics.

In Reference 3, Mayhew extolled the benefits of transforming the Neal-Smith boundaries into the frequency domain in a form similar to MIL-F-8785B. A problem with the requirements in MIL-F-8785B, however, is that current advanced flight control systems often produce airplane dynamics without an identifiable short-period mode. This problem is overcome by using the parameters of an equivalent system representation:

$$\frac{\dot{\theta}}{F_s} = \frac{k\, e^{-A_E S}\,(T_E s + 1)}{\frac{S^2}{\omega_E^2} + \frac{2\zeta_E S}{\omega_E} + 1}$$

Note that this includes an equivalent time delay, A_E, which is not a parameter in the requirements of MIL-F-8785B. The data base included lags and time delays which are assumed to be small enough to not affect the results. The time delay is necessary, in general, to match the dynamics of actual systems.

The objective of this paper is to compare the LAHOS data [4] with the criteria proposed in Reference 3 for revising the short-period requirements in MIL-F-8785B. The original proposals are no longer being considered for the draft MIL-F-8785C; this paper presents the reasons. Additionally, this paper should complement other papers at this symposium by addressing proposed criteria not considered by others.

THE MAYHEW CRITERION

The criteria derived by Mayhew, shown in Figure 1, are maximum and minimum values of equivalent frequency, ω_E, as functions of equivalent damping ratio, ζ_E, equivalent time delay, A_E, and equivalent numerator time constant, $1/T_E$. These boundaries were obtained by matching frequency responses of the equivalent transfer function above with the Neal-Smith tracking performance standards of Figure 2. In principal, the four parameters are all interrelated and may be traded off in terms of acceptable tracking performance and pilot rating.

The experimental data in Reference 2 are oriented towards Class IV (fighter) configurations in Category A Flight Phases. It is interesting to inspect the trends of these results first. The expression for the maximum frequency has a singularity when

$$A_E = \zeta_E/2.4$$

which can be called a critical value. In this region, the maximum frequency tends to zero for A_E slightly less than the critical value while for A_E slightly greater than the critical value the maximum frequency approaches infinity. A more reasonable result would be for the maximum acceptable frequency to increase with both damping ratio and time delay. A more practical aspect of this singularity is that the requirement is essentially undefined when the maximum allowable frequency is near zero. By contrast, the variation of the minimum frequency with time delay is not unreasonable for time delays less than a critical value of 0.286 seconds, when the 'minimum' frequency goes to infinity. This is compared with a value of 0.25 seconds more recently suggested by Hodgkinson [5] to retain Level 3 flying qualities.

At the risk of trying to milk a dead cow, it may be interesting to look at the form of the Category A, Class IV requirement in more detail. If we consider T_E to be constant, and the true value is approximately constant for the LAHOS data, then the frequency limits become tradeoffs of equivalent damping ratio vs equivalent time delay. For a given value of equivalent damping ratio, as time delay increases from zero the maximum and minimum values of frequency converge to a simple point which can be interpreted as the maximum time delay for Level 1 characteristics, with further increases in time delay being meaningless. This maximum allowable time delay is shown in Figure 3 as a function of equivalent damping ratio. Note that there is no solution for Level 1 flying qualities for damping ratios less than approximately 0.65. It is an interesting coincidence that no configuration with less than this value received a Level 1 pilot rating in Reference 2, even though the requirements in MIL-F-8785B is a minimum damping ratio of 0.35. If the criteria in Figure 1 <u>were</u> correct, then

Figure 3 shows that the allowable time delay would increase with increasing damping ratio far beyond the value of 0.1 seconds currently proposed as the limit. Also shown on the curve is the corresponding equivalent short-period frequency that goes with the limit time delay. These considerations are interesting but academic in light of the correlation results shown in the next section.

Data Comparison

The equivalent system parameters determined by John Hodgkinson [6] were compared with both Category C and A requirements from Figure 1. The equivalent system parameters are repeated here for reference as Table 1. Table 2 presents a summary of the results using T_E fixed at a value given by the airplane L_α. The following points are apparent:

(i) The six Level 1 configurations are correctly identified by the Cat. C criteria.

(ii) Of the remaining 40 configurations, only 10 are correctly identified as being worse than Level 1 by the Cat. C criteria.

(iii) One half of the total number of configurations are passed as Level 1 by the Cat. C criteria, while the pilot ratings are worse than Level 1.

(iv) The Category A requirements would predict five of the Level 1 configurations to be worse than the actual rating.

(v) The Cat. A requirements are undefined for the majority of configurations worse than Level 1 which would be assessed as Level 1 by the Cat. C requirements.

The Category C criteria thus appear to predict the Level 1 configurations far better than the Category criteria. This contradicts the suggestion by Smith [4] that the landing task may need to be considered a Category A Flight Phase. This suggestion is supported by the analysis of the LAHOS data by

Hodgkinson [6]. Now, we may consider the undefined parts of the Category A criteria to be indicative of "worse than Level 1" characteristics. With that interpretation the Category A criteria do predict those cases reasonably well. In total, however, neither the Category A nor the Category C criteria can be judged acceptable.

For some configurations, another formulation is required in order to achieve a better match of the equivalent and the actual frequency responses. In this case T_E is considered a free parameter (of the transient response) unrelated to the steady-state value of airplane L_α, termed the L_α - free cases. A summary of the comparison of these equivalent system parameters with the Mayhew criteria is presented in Table 3. As can be seen, the results for the Category C criteria are virtually unaffected by freeing L_α. The Category A results, if anything, are made worse. In comparison with the criteria under consideration here, there is no apparent benefit from freeing T_E to achieve a better equivalent system match.

Conclusions

In principal, there is a certain aesthetic benefit from combining all the parameters affecting a particular response into one requirement, provided it is in a useful form. Mayhew attempted to formulate a requirement for short-term pitch control that combined the numerator and denominator terms of the equivalent transfer function of pitch attitude to stick force input. In the LAHOS experiment the pilot adjusted the feel system first of all so that, in general, it should not be a significant factor in the pilot ratings. For the application discussed herein, therefore, the Mayhew criteria should be the only discriminant necessary to correlate the ratings. It is judged that the results do not support the use of these criteria in the flying qualities specification, at this time. One of the advantages claimed for the proposed criteria was the possibility of empirically modifying the requirements as more data was acquired. In practice, adjusting four-dimensional boundaries has not proved to be a simple task.

The proposed MIL-F-8785C, which is currently being drafted, revised the short-period requirements by specifically calling out equivalent short-period frequency and equivalent short-period damping ratio. The numerical requirements are the same as in MIL-F-8785B. In addition to this change, limits on allowable equivalent time delay are also specified (in paragraph 3.5.3). Thus, this revision maintains the existing data base which probably included finite (but unknown) lags or effective time delays. The boundaries in MIL-F-8785B are, therefore, assumed to be valid if the lag or time delay does not become too large. Limits on the equivalent time delay have now been specified. Finally, no method is specified for generating the equivalent system - the specification will require only that the method be approved by the procuring activity.

References

1. Chalk, C.R. et al, "Background Information and User Guide for MIL-F-8785B, 'Military Specification - Flying Qualities of Piloted Airplanes'", AFFDL-TR-69-72, Aug 1969

2. Neal, T.P. and Smith, R.E., "An In-Flight Investigation to Develop Control System Design Criteria for Fighter Airplanes", AFFDL-TR-70-74, Dec 1970

3. "Proposals for Revising MIL-F-8785B 'Flying Qualities of Piloted Airplanes'", AFFDL-FGC Working Paper, Feb 1978

4. Smith, R.E., "Effects of Control System Dynamics on Fighter Approach and Landing Longitudinal Flying Qualities", AFFDL-TR-78-122, March 1978

5. Hodgkinson, J., "The Application of Equivalent Systems to MIL-F-8785B", published in AFFDL-TR-78-171, Dec 1978

6. Johnston, K.A. and Hodgkinson, J., "Flying Qualities Analysis of an In-Flight Simulation of High Order Control System Effects on Fighter Aircraft Approach and Landing", McDonnell Douglas Co. Report Number MDC-A5596, Dec 1978

	L_{α_e} Fixed											L_{α_e} Free												
Configuration	τ (sec)	ζ_{SP_e}	ζ_{SP_e} Level	ω_{SP_e} (rad/sec)	Level of ω_{SP_e} for Category A	Level of ω_{SP_e} for Category C	L_{α_e}	n_z/α (g/rad)	Phase Lag at ω_{SP_e} (deg)	Level	Mismatch	τ (sec)	ζ_{SP_e}	ζ_{SP_e} Level	ω_{SP_e} (rad/sec)	Level of ω_{SP_e} for Category A	Level of ω_{SP_e} for Category C	L_{α_e}	n_z/α (g/rad)	Phase Lag at ω_{SP_e} (deg)	Level	Mismatch	PR (C-H) Overall	PR (C-H) Approach
1-A	0.028	1.18	1	1.50	1	1	0.71	4.50	2.4	1-2	26.3	0.028	1.77	2	0.87	2-3	3	0.22	1.36	1.4	1-2	21.0	6	6
1-B	0.026	1.04	1	1.30	1	1			2.0	1-2	23.5	0.028	1.41	2	0.83	2-3	2	0.26	1.66	1.3	1-2	18.8	5	–
1-C	0.035	0.88	1	1.13	2-3	1			2.3	1-2	11.7	0.037	1.04	1	0.86	2-3	2	0.38	2.41	1.8	1-2	8.9	4,4	–
1-1	0.067	0.74	1	1.00	2-3	1			3.8	1-2	0.2	–	–	–	–	–	–	–	–	–	–	–	4,4	2
1-2	0.147	0.69	1	0.96	2-3	1			8.0	1-2	6.2	–	–	–	–	–	–	–	–	–	–	–	5	–
1-3	0.197	0.57	1	0.84	4	2-3			9.6	1-2	59.6	0.143	0.71	1	1.75	4	4	6.39*	40.31	14.3	1-2	11.8	9,10	6,6
1-4	0.228	0.49	1	0.72	2-3	2-3			9.4	1-2	161.8	0.127	0.69	1	1.48	4	4	11.99*	75.58	10.7	1-2	6.4	10	–
1-6	0.161	0.74	1	1.00	2-3	1			9.2	1-2	0.3	–	–	–	–	–	–	–	–	–	–	–	5,–	2,5
1-8	0.234	0.73	1	2.31	1	1			31.1	3	172.3	0.230	0.67	1	1.15	2-3	1	1.08	6.79	15.2	1-2	12.4	8	5
1-11	0.238	0.75	1	1.00	2-3	1			13.8	1-2	0.4	–	–	–	–	–	–	–	–	–	–	–	9	5
2-A	0.034	0.65	1	3.48	1	1			6.7	1-2	18.8	0.043	0.78	1	3.34	1	2	0.53	3.36	8.2	1-2	8.0	4,6	2,3
2-C	0.043	0.64	1	2.69	1	1			6.6	1-2	5.9	–	–	–	–	–	–	–	–	–	–	–	4,1.5,1.5,3	3
2-1	0.067	0.57	1	2.30	1	1			8.8	1-2	0.2	–	–	–	–	–	–	–	–	–	–	–	2,2	3
2-2	0.143	0.53	1	2.16	1	1			17.7	1-2	4.3	–	–	–	–	–	–	–	–	–	–	–	4,4.5	2,2
2-3	0.186	0.49	1	1.84	1	1			19.5	1-2	36.4	0.174	0.38	1	2.11	1	1	1.18	7.42	21.0	1-2	22.5	6	–
2-4	0.210	0.49	1	1.50	1	1			18.1	1-2	88.7	0.173	0.32	2	2.24	2-3	1	2.86*	18.07	22.2	1-2	32.9	9,–,–	–,5,3
2-6	0.161	0.57	1	2.31	1	1			21.3	1-2	0.3	–	–	–	–	–	–	–	–	–	–	–	5	1.5
2-7	0.193	0.56	1	2.28	1	1			25.2	1-2	2.3	–	–	–	–	–	–	–	–	–	–	–	7,6	4,3
2-9	0.285	0.46	1	2.00	1	1			32.6	3	67.2	0.274	0.36	1	2.25	1	1	1.12	7.08	35.2	3	54.0	10	5
2-10	0.332	0.39	1	1.71	1	1			32.5	3	202.4	0.261	0.22	3	2.71	2-3	2-3	5.45*	34.36	40.6	3	114.6	10	6
2-11	0.240	0.58	1	2.33	1	1			31.9	3	0.3	–	–	–	–	–	–	–	–	–	–	–	8	4
3-C	0.030	0.27	2	2.38	1	1			4.0	1-2	18.2	0.035	0.31	2	2.32	1	1	0.59	3.71	4.7	1-2	11.1	2,5	–,5
3-0	0.067	0.14	4	2.10	1	1			8.4	1-2	0.2	–	–	–	–	–	–	–	–	–	–	–	4,5	–,–
3-1	0.067	0.25	2	2.20	1	1			8.8	1-2	0.2	–	–	–	–	–	–	–	–	–	–	–	4,7,5	–,–,5
3-2	0.143	0.24	3	2.13	1	1			17.5	1-2	7.4	–	–	–	–	–	–	–	–	–	–	–	7,–	–,6
3-3	0.202	0.23	3	1.95	1	1			22.5	1-2	74.2	0.187	0.17	3	2.12	1	1	1.17	7.39	22.7	1-2	42.4	10	–,7
3-6	0.161	0.25	2	2.21	1	1			20.3	1-2	0.3	–	–	–	–	–	–	–	–	–	–	–	7,6	5.5
3-7	0.194	0.25	3	2.19	1	1			24.4	1-2	2.4	–	–	–	–	–	–	–	–	–	–	–	8	5
4-C	0.057	1.30	1	2.58	1	1			8.5	1-2	0.9	–	–	–	–	–	–	–	–	–	–	–	3,3	1.5,2
4-0	0.067	1.23	1	2.10	1	1			8.1	1-2	0.2	–	–	–	–	–	–	–	–	–	–	–	6	–
4-1	0.067	1.06	1	2.00	1	1			7.7	1-2	0.2	–	–	–	–	–	–	–	–	–	–	–	2	–
4-3	0.172	0.81	1	1.46	1	1			14.4	1-2	18.6	0.159	0.61	1	2.07	1	1	1.75	11.02	18.6	1-2	10.0	5,8,7	–,5,2
4-4	0.190	0.72	1	1.15	2-3	1			12.5	1-2	41.8	0.135	0.65	1	2.58	4	2-3	7.63*	48.14	20.0	1-2	7.1	7,6,–	4,3,5
4-6	0.161	1.06	1	2.01	1	1			18.5	1-2	0.3	–	–	–	–	–	–	–	–	–	–	–	4	1.5
4-7	0.191	1.03	1	1.97	1	1			21.5	1-2	2.1	–	–	–	–	–	–	–	–	–	–	–	3	3
4-10	0.314	0.64	1	1.33	1	1			24.0	1-2	151.1	0.218	0.44	1	2.88	4	2-3	12.94*	81.59	36.0	3	24.8	9	6
4-11	0.240	1.07	1	2.03	1	1			27.9	1-2	0.3	–	–	–	–	–	–	–	–	–	–	–	8	3
5-1	0.067	0.54	1	3.90	1	1			15.0	1-2	0.2	–	–	–	–	–	–	–	–	–	–	–	7,5	–,4
5-3	0.174	0.54	1	2.95	1	1			29.3	1-2	19.1	0.167	0.45	1	3.10	1	1	0.92	5.80	29.6	1-2	13.2	8,6,4,5	2,3,4,3
5-4	0.193	0.63	1	2.35	1	1			26.0	1-2	42.4	0.181	0.46	1	2.72	1	1	1.21	7.62	28.2	1-2	25.4	6	2
5-5	0.206	0.83	1	1.77	1	1			20.9	1-2	64.8	0.142	0.41	1	3.58	2-3	1	7.17*	45.18	29.0	1-2	10.3	7	2
5-6	0.159	0.52	1	3.90	1	1			35.6	3	0.4	–	–	–	–	–	–	–	–	–	–	–	6	3
5-7	0.190	0.52	1	3.82	1	1			41.5	3	1.9	–	–	–	–	–	–	–	–	–	–	–	6	2
5-11	0.240	0.54	1	3.95	1	1			54.3	3	0.3	–	–	–	–	–	–	–	–	–	–	–	7	3
6-1	0.321	0.56	1	1.30	1	1			23.9	1-2	181.7	0.240	0.39	1	2.53	4	2-3	8.03*	50.63	34.7	3	37.5	10	–
6-2	0.084	0.78	1	1.74	1	1			8.4	1-2	1.7	–	–	–	–	–	–	–	–	–	–	–	2	–

Notes

1. Configurations are defined in AFFDL-TR-78-122
2. Equivalent short period pitch rate transfer function for stick force input is

$$\frac{\dot{\theta}}{F_{ST}} = \frac{K_{\dot{\theta}}(T_{\theta_{2_e}} S + 1)e^{-\tau S}}{S^2 + 2\zeta_{SP_e}\omega_{SP_e} S + \omega_{SP_e}{}^2}$$

3. Levels and categories are from MIL-F-8785B(ASG)
4. L_{α_e} was freed in the matching procedure only if the mismatch exceeded 10 with L_{α_e} fixed
5. PR(C-H) - pilot rating (Cooper-Harper)
6. L_{α_e} marked with asterisk indicates "galloping L_{α}"

GP79 0186 9

TABLE 1
EQUIVALENT SYSTEM PARAMETERS FOR LAHOS DATA (FROM MDC A5596)

FLIGHT PHASE	CLASS	UNDAMPED NATURAL FREQ.	
		MAX	MIN
CAT A	I & IV	$40\left(\frac{1}{3T_E}\right)^{\frac{1.2}{\zeta_E - 2.4A_E}}$	HIGHER OF $\frac{1.8}{\zeta_E(1-3.5A_E)}$ AND $\left(\frac{3}{1-3.5A_E}\right)\left(\frac{1}{2.5T_E}\right)^{\zeta_E/1.85}$
	II & III	HIGHER OF $10\left(\frac{1}{3T_E}\right)^{.52/\zeta_E}$ AND $40\left(\frac{1}{3T_E}\right)^{1.2/\zeta_E}$	HIGHER OF $\frac{0.6}{\zeta_E(1-1.7A_E)}$ AND $\frac{1.8}{1-1.7A_E}\left(\frac{1}{2T_E}\right)^{\zeta_E/2.3}$
CAT B & C	ALL	HIGHER OF $10\left(\frac{1}{3T_E}\right)^{.52/\zeta_E}$ AND $40\left(\frac{1}{3T_E}\right)^{1.2/\zeta_E}$	LOWER OF $\frac{2}{1-.7A_E}$ AND $\frac{1.1}{1-.7A_E}\left(\frac{1}{2T_E}\right)^{\zeta_E/3.2}$ BUT NO LOWER THAN $\frac{.37}{\zeta_E(1-.7A_E)}$

FIGURE 1. EQUIVALENT SHORT-PERIOD CRITERIA (MAYHEW, REF. 3)

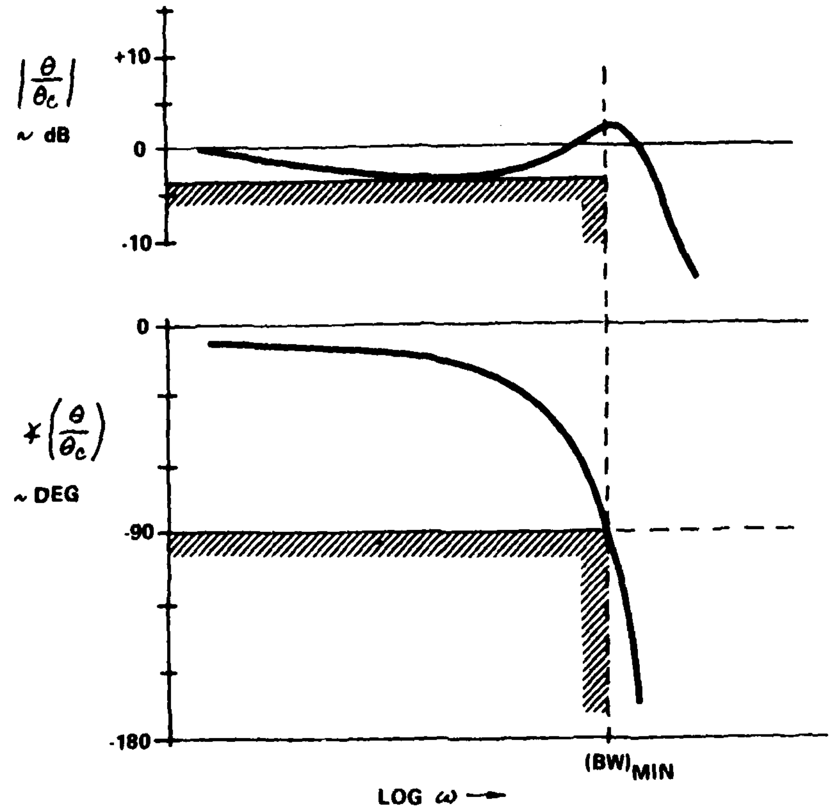


Figure 2. Tracking Performance Standards Used in the Analysis.

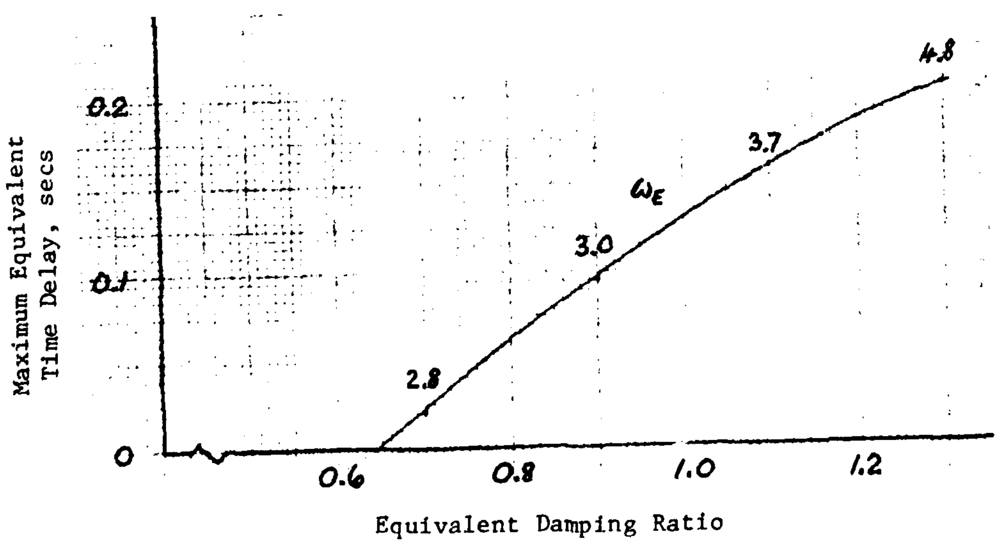


Figure 3. Maximum Time Delay vs Damping Ratio

TABLE 2. Summary of Comparisons - L_α Fixed

ACTUAL PILOT RATING	RATING PREDICTED BY MAYHEW	NUMBER OF CONFIGURATIONS	
		CAT. C	CAT. A
1	1	6	1
1	WORSE	0	5
WORSE	1	23	3
WORSE	WORSE	10	9
	UNDEFINED	7	28

TABLE 3. Summary of Comparisons - L_α Free

ACTUAL PILOT RATING	RATING PREDICTED BY MAYHEW	NUMBER OF CONFIGURATIONS	
		CAT. C	CAT. A
Level 1	Level 1	6	1
Level 1	WORSE	0	1
WORSE	Level 1	24	1
WORSE	WORSE	9	16
	UNDEFINED	7	27

Implications of Time Response Matching to Equivalent Systems and the Neal-Smith Criterion

by

J. M. Stifel
Naval Air Development Center
Warminster, Pennsylvania

Abstract

A method of obtaining equivalent systems based on matching time histories of different order systems when subjected to damped sinusoidal inputs is presented. The reason for considering such inputs is related to the approximation of arbitrary aperiodic inputs. The region in the Laplace domain within which human pilots are capable of operating is related to the similar frequency range currently in use in frequency domain techniques. Examples of the solution technique are presented. The results appear to have significant implications regarding the similarity and validity of frequency response matching and the Neal-Smith Criterion.

Introduction

The concept of an equivalent system is based upon the close similiarity in the output of two linear systems of different order when subjected to identical inputs. The ultimate test of equivalency, from a flying qualities standpoint, is the ability to evoke identical pilot ratings. Current methods of determining equivalent systems assume that maintaining a close similarity of frequency response implies a close similarity in time response. Since the technique has met with significant success in predicting pilot ratings the assumption must have merit. Consider however that the frequency response represents only part of the total time response (the forced response) and the response to only a special class of the general input

$$x(t) = Ae^{\sigma t} \sin(\omega t+\emptyset)$$

for which $\sigma = 0$. The link between frequency response matching and the general similarity of time response to all such inputs is not immediately clear. This is an issue which bears directly on basic equivalance and on the validity of currently suggested methods, and is the subject of the hypothesis developed here.

Consideration of Laplace Domain Inputs

Linear control theory states that the general solution to the differential equations describing the system requires the input $x(t)$ to be of the form shown and the ouput to be of the form

$$y(t) = \underbrace{GAe^{\sigma t} \sin(\omega t + \emptyset + \theta)}_{\text{Forced Response}} + \underbrace{\Sigma Be^{j\psi} e^{rt}}_{\text{Free Response}}$$

Where G and θ are the magnitude and phase of the transfer function and are functions of $s = \sigma + j\omega$. The free response r's are the transfer function pole locations and the complex constants, $Be^{j\psi}$, are determined by initial quiescent conditions. The linearity of the system allows an arbitrary input to be approximated by any number of functions of the form x(t). If we consider how well the irregular aperiodic inputs which a human operator might make to a system may be approximated by a linear combination of functions of the form x(t), it will be apparent that restricting consideration only to those points for which $\sigma = 0$ does not necessarily give the best approximation.

The Taylor's series expansion of the input function equates the value of the function and the series as well as their derivatives at a point in time to obtain an approximation to the function in the vicinity of that point. Similarly we may equate the value of the function and its first derivative at a number of time points to obtain a series of the form x(t) valid over a given time interval. These equalities will be referred to as similarity conditions. The number of these conditions which may be enforced is related to the number of terms in the Taylor's series and therefore the accuracy of the approximation. Writing x(t) in complex form

$$x(t) = \frac{\Sigma A e^{j\phi}}{2j} e^{st}$$

and imposing similarity conditions on x(t) and its derivative x'(t) at i points yields a system of constraint equations.

$$\begin{bmatrix} x(t_1) \\ x(t_2) \\ \vdots \\ x(t_i) \end{bmatrix} = \begin{bmatrix} e^{s_1 t_1} & e^{s_2 t_1} & \cdots\cdots & e^{s_i t_i} \\ e^{s_1 t_2} & e^{s_2 t_2} & \cdots\cdots & e^{s_i t_2} \\ \vdots & \vdots & & \vdots \\ e^{s_1 t_i} & e^{s_2 t_i} & \cdots\cdots & e^{s_i t_i} \end{bmatrix} \begin{bmatrix} A_i e^{j\phi_1}/2j \\ A_2 e^{j\phi_2}/2j \\ \vdots \\ A_i e^{j\phi_i}/2j \end{bmatrix}$$

$$\begin{bmatrix} x'(t_1) \\ x'(t_2) \\ \vdots \\ x'(t_i) \end{bmatrix} = \begin{bmatrix} s_1 e^{s_1 t_1} & s_2 e^{s_2 t_1} & \cdots\cdots & s_i e^{s_i t_1} \\ s_1 e^{s_1 t_2} & s_2 e^{s_2 t_2} & \cdots\cdots & s_i e^{s_i t_2} \\ \vdots & \vdots & & \vdots \\ s_1 e^{s_1 t_i} & s_2 e^{s_2 t_i} & \cdots\cdots & s_i e^{s_i t_i} \end{bmatrix} \begin{bmatrix} A_1 e^{j\phi_1}/2j \\ A_2 e^{j\phi_2}/2j \\ \vdots \\ A_i e^{j\phi_i}/2j \end{bmatrix}$$

in which A_i, σ_i, ω_i, ϕ_i are unknown. Considering that each equation has a real and imaginary part, these represent 4_i equations. Thus with the complete input form it is possible to enforce 2_i similarity conditions.

If however we restrict consideration only to S values for which $\sigma = 0$, we eliminate both σ and ω as variables, reduce the number of similarity constraints to i and therefore reduce the accuracy of the approximation. The input form becomes

$$x(t) = \Sigma A \sin(\omega t + \phi)$$

Each term of which repeats when

$$\omega t = 2\pi n$$

For all terms to repeat at the same time:

$$t = \frac{2\pi n}{\omega_1} = \frac{2\pi m}{\omega_2} = \text{etc.}$$

Which means only that the ratios of the frequencies must be rational numbers.

$$\frac{\omega 1}{\omega_2} = n/m$$

Therefore, to any desired accuracy, the frequencies are always integral multiples of a common base frequency and the input approximation:

$$x(t) = \Sigma A \sin(n\pi t/L + \phi)$$

becomes the general Forier series which repeats every 2L. To approximate on aperiodic series a lower limit on 2L equal to the time interval over which the approximation must hold must be imposed to prevent the series from repeating. The frequencies in the dampled sine series have the same relationship except that no lower limit exists on 2L making the frequencies in effect independent of L and each other.

Thus, setting $\sigma = 0$ also eliminates ω as a variable and cuts the number of similarity conditions that may be imposed in half. The exception is when the input function really is periodic, then $\sigma = 0$ for all terms. It is now clear that examining the input/output similarity between two systems only along the $j\omega$ axis in the Laplace domain reveals the equivalency of the systems to periodic input signals only.

Just as in frequency response methods it is necessary to determine the range of interest of the Laplace variable, S. If the frequency limits are related to pilot reaction speed by the time between peaks, the limit is easily extendable to the first peak of a damped sinusoid which occurs at time

$$t_o = \frac{1}{\omega} \tan^{-1} \frac{-\omega}{\sigma}$$

Values for σ and ω which hold t_o constant represents the boundary of the region in which human pilots are capable of operating. Two systems should respond similarly to all input signals in this region to be equivalent. The boundary for $t_o = .157$ sec. corresponding to an upper frequency limit of 10 rad/sec. is shown in figure 1 along with a number of test signal points which span the region.

EXTENSION OF FREQUENCY RANGE INTO THE LAPLACE DOMAIN

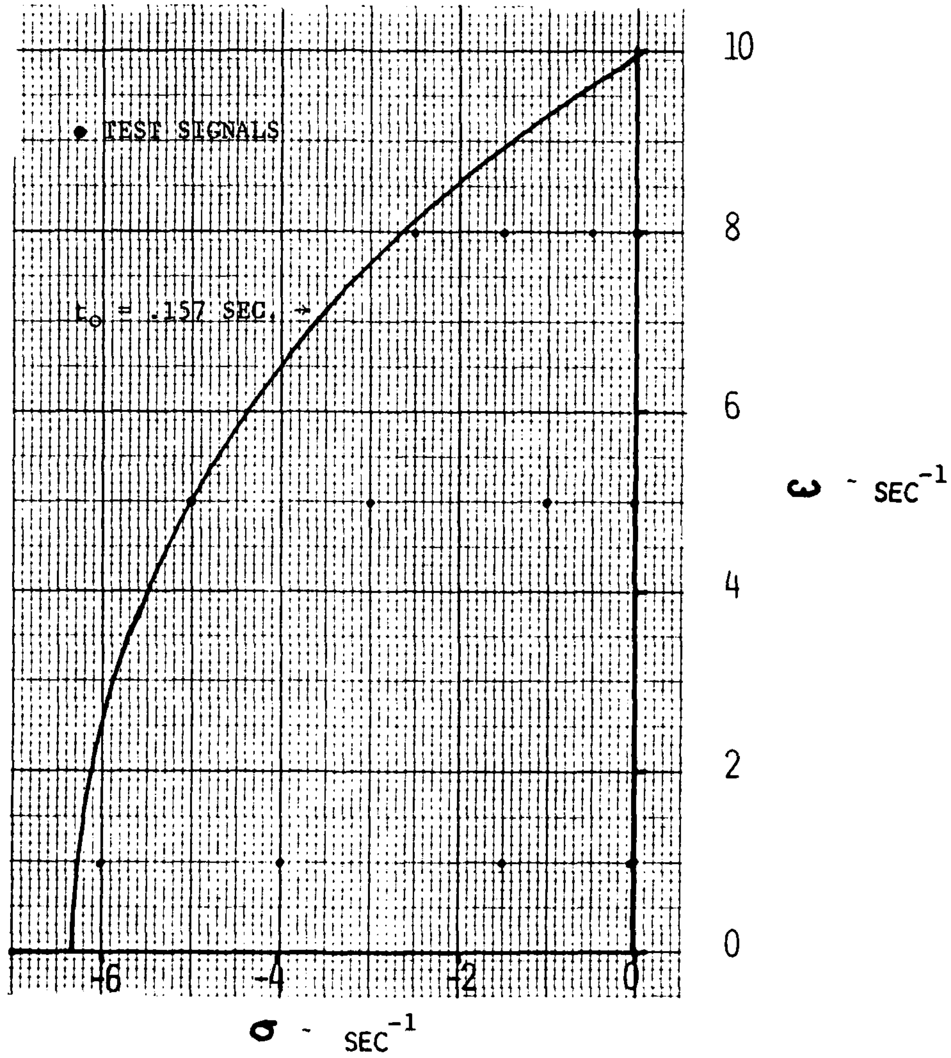


FIGURE 1

Time Response Matching

It is possible to determine equivalent system parameters by enforcing a minimum acceptable degree of similarity between the time responses of the high and low order systems when both are subjected to a common damped sinusoidal input. A number of methods including a minimum squared error fit may be used to accomplish this. The method chosen here is to impose a number of similarity conditions on the equivalent system output:

$$y(t) = GAe^{\sigma t} \sin (\omega t + \theta) + \Sigma Be^{j\psi} e^{rt}$$

and its derivative:

$$y'(t) = GAe^{\sigma t} \{\sigma \sin(\omega t+\theta) + \omega \cos(\omega t+\theta)\} + \Sigma rBe^{j\psi} e^{rt}$$

at a number of points in time. Doing so produces a number of non-linear algebraic equations in an equal number of unknowns. That number is related to the order of the nth/mth equivalent by:

$$\text{no. of unknowns} = 1 + n + 2\,m$$

This number of similarity conditions may then be enforced on the equivalent system output. The question remains of what similarity conditions to enforce. The constants, $Be^{j\psi}$, are determined by the initial conditions.

$$y(o) = 0,\ y'(o) = 0,\ ---,\ y^{m-1}(o) = 0$$

and must always be enforced. This leaves 1+n+m similarity constraints to be enforced at non zero time. The choice for these must lie in assumptions about what gross characteristics of the output function are most significant to human pilots. If it is assumed that the pilot will interpret the initial peak as the systems response to his input and the remainder as characteristic of the residual dynamics of the system, then applying similarity conditions at the initial peak and at the subsidence time are conditions to be met. These are felt to be only the minimum conditions for obtaining good correlation with pilot ratings. It is also clear that to meet the four required similarity conditions with n less than or equal to m, n must be 1 and m must be 2.

Therefore, the minimum acceptable low order system is 1st/2nd. For a 1st/2nd order system the constraint equations become:

$$r = a \pm jb$$

$$o = GA \sin \theta + B \sin \psi$$

$$o = GA (\sigma \sin \theta + \omega \cos \theta) + B (a \sin \psi + b\cos \psi)$$

$$y(t_1) = GAe^{\sigma t_1} \sin (\omega t_1+\theta) + B e^{at_1} \sin (bt_1 + \psi)$$

$$y(t_2) = GAe^{\sigma t_2} \sin (\omega t_2+\theta) + B e^{at_2} \sin (bt_2 + \psi)$$

$$o = GAe^{\sigma t_1} \left[\sigma \sin(\omega t_1+\theta) + \omega \cos(\omega t_1+\theta)\right] + Be^{at_1}\left[a\sin(bt_1+\psi)+b\cos(bt_1+\psi)\right]$$

$$y'(t_2) = GAe^{rt_2}\left[\sigma \sin(\omega t_2+\theta) + \omega \sin(\omega t_2+\theta)\right] + Be^{at_2} \left[a\sin(bt_2+\psi) + b\cos(bt_2+\psi)\right]$$

which may be solved numerically for:

$G, \theta, B, \psi, a, b.$

The equations have a different form if real roots are required. The numerator zero and gain are determined from

$$K\ (S+a_3) = Ge^{j\theta}\ (S^2 + 2as + a^2+b^2)$$

If the value of $s = \sigma+j\omega$ is altered the known coefficients of the unknowns in the above equations are altered. In general this means that the solutions for the unknowns depend on the value of s choosen, that is, the input function.

If this were not true and the equivalent system parameters did not vary over the laplace domain, they could be determined as well by imposing a single similarity condition for a number of input signals as by imposing a number of similarity conditions for a single input signal. The magnitude and phase of the transfer function at $\sigma = 0$ represents the same condition as the subsidence time at non zero σ. Matching the $j\omega$ Bode is then equivalent to enforcing the similarity of the long term time response for many different input signals. The theory implies the success of that technique depends on the equivalent system parameters variations being negligible throughout the pilot operating region. Failure to obtain a close match of frequency response implies failure to find a single set of equivalent system parameters capable of simulating the long term response of the system over the frequency range of interest. Provided that the frequency match solution method is reliable, this is a direct indication that the equivalent system parameters can not be considered constant even along the $j\omega$ axis. Since frequency response matching does not answer the question of how much the parameters vary it is not known if they vary beyond acceptable limits. Therefore failure to obtain a good frequency match may not necessarily be sufficient reason to discard the system.

Artificial Time Delays

Time delays were instituted to remedy the inability of frequency matching techniques to obtain acceptable phase angle matches. As justification it was reasoned that the time delay accounted for high frequency lags.

From the viewpoint of time response matching use of artificial time delays is mostly negative. All the required similarity conditions can be met without them. Time delays shift the initial conditions to a time greater than zero while adding the ability to enforce one additional similarity condition. But while one is gained two are lost in shifting the initial conditions. In addition the equivalent parameters must be adjusted to allow for a quicker rise to the initial peak. If the time delay is small, this adjustment may be similarly small and the shift in initial conditions may go unnoticed by the pilot. The result may even be better, in the minimum squared error sense, than the same order system without time delay. But the time delay is in effect increasing the order of the system beyond the minimum form. Use of a 2nd/2nd order equivalent could achieve the same or better result without disturbing the initial conditions. There is then an implication that the use of artificial time delays may not be desirable.

Examples of Time Response Matching

The LAHOS 1-4 configuration of reference 2 was subjected to the input signals of Figure 1. Figures 2 and 3 show time response comparisons between the high order system and the time response matched equivalents for several of these inputs. The initial peak magnitude of each input was held at unity. Figure 4 shows the variations in the equivalent system parameters compared to the $L\alpha$ free frequency matched equivalent.

The time histories demonstrate that good time response matches are obtainable for a variety of inputs using the suggested method. Since good time response matches may be obtained the concept of an equivalent system is strengthened. The variation in the equivalent system parameters with input damping suggests that the invariance assumption is very good at low frequencies at least for this system. At higher frequencies however the assumption breaks down. Large variations with frequency are also indicated. Further the $L\alpha$ free frequency matched equivalent, which has a cost function less than 10, does not closely approximate all the time response matched equivalent system parameters in the region where the assumption appears to hold. This is probably due to averaging effects over the whole frequency range, including the region where the assumption of invariance does not hold. The distorting effects of the time delay could also be a contributing factor.

Neal and Smith Criteria

The Neal and Smith criteria of reference 1 is also a frequency domain technique. As such the invariance of parameters is implied just as in frequency response matching. There are however stronger similarities between the two methods. The main difference is the low order system is 0/2nd order and fixed. The fact that this is less than the minimum 1st/2nd order indicated by time response matching does not invalidate the approach since its response is the standard against which the high order system is measured. That is the high order system is the equivalent. Variables are added to the high order equivalent by adding variable pilot compensation:

$$K_p \frac{(T_1S+1)}{(T_2S+1)} e^{-.3S}$$

Since the high order system has only three variables, only three non-initial similarity conditions may be met. Thus the pilot compensation form is inadequate to impose time response similarity according to the time response matching method.

Before the resonance and crossover frequencies of the 0/2nd order "optimum" can be related to the high order system the order of the pilot compensation must be increased so that minimum acceptable similarity of time response matches may be obtained. Once this is done the validity of the method still depends on invariance of the equivalent system parameters.

TIME RESPONSE COMPARISON

LAHOS 1 - 4 VS. TIME MATCHED EQUIVALENT

$\omega = 1$ RAD. / SEC.

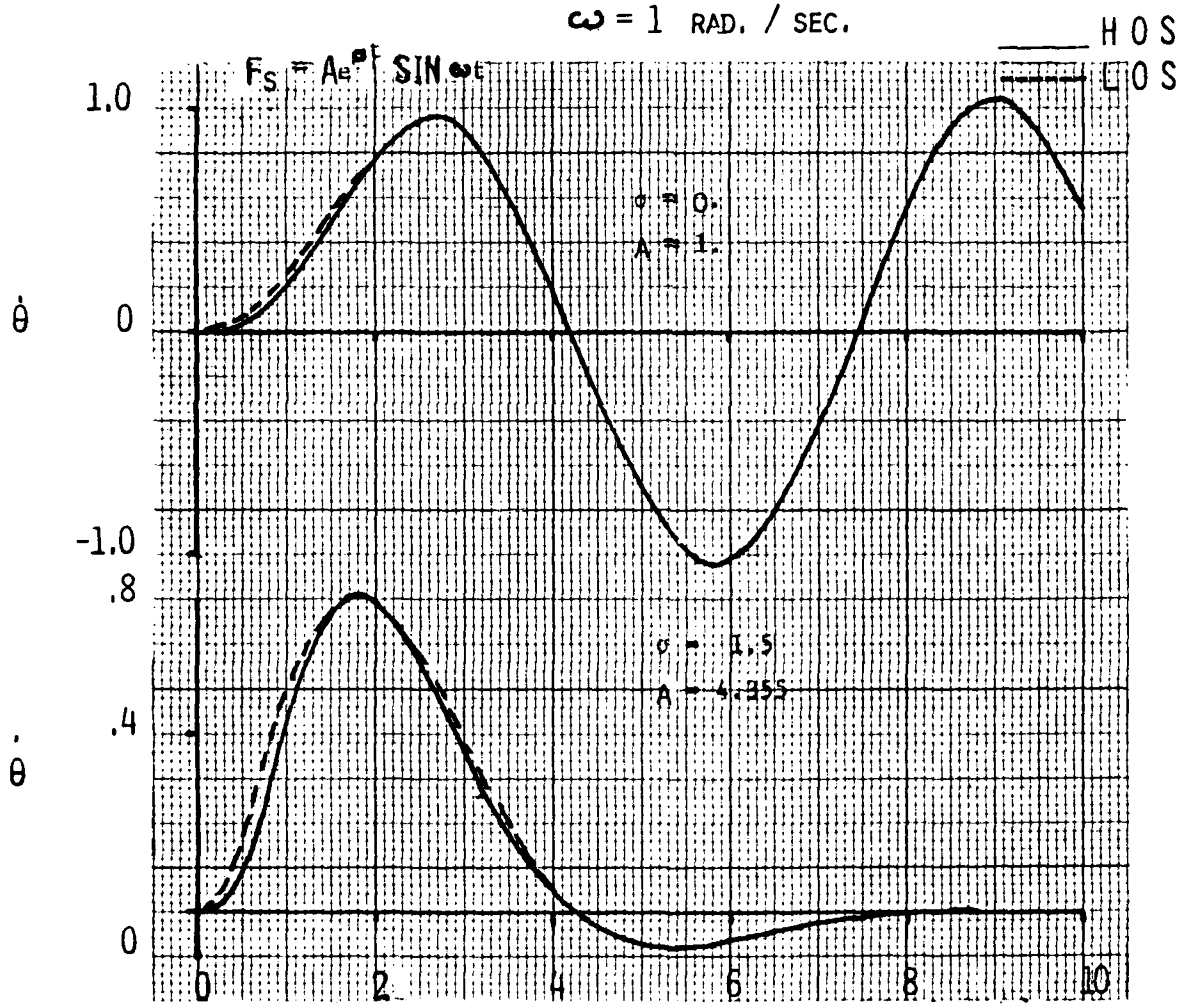


FIGURE 2.

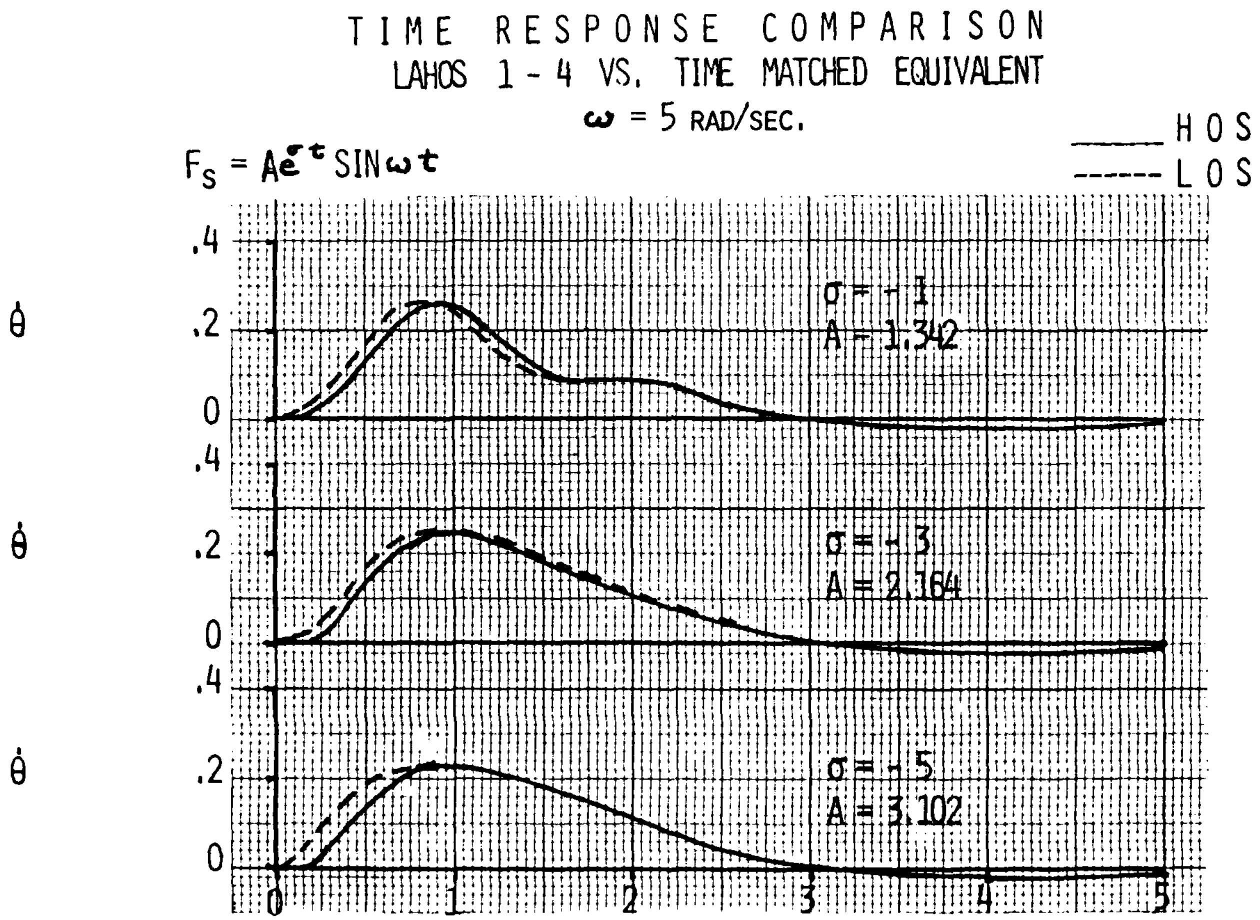

TIME RESPONSE COMPARISON
LAHOS 1 - 4 VS. TIME MATCHED EQUIVALENT
ω = 5 RAD/SEC.
$F_S = Ae^{\sigma t} \mathrm{SIN}\, \omega t$
HOS
LOS
$\dot{\theta}$
$\dot{\theta}$
$\dot{\theta}$
.4
.2
0
.4
.2
0
.4
.2
0
σ = -.1
A = 1.342
σ = -.3
A = 2.164
σ = -.5
A = 3.102
0
1
2
3
4
5

FIGURE 3.

VARIATION OF EQUIVALENT SYSTEM
PARAMETERS WITH INPUT DAMPING
BASED ON TIME RESPONSE MATCHING

LAHOS 1 - 4 CONFIGURATION

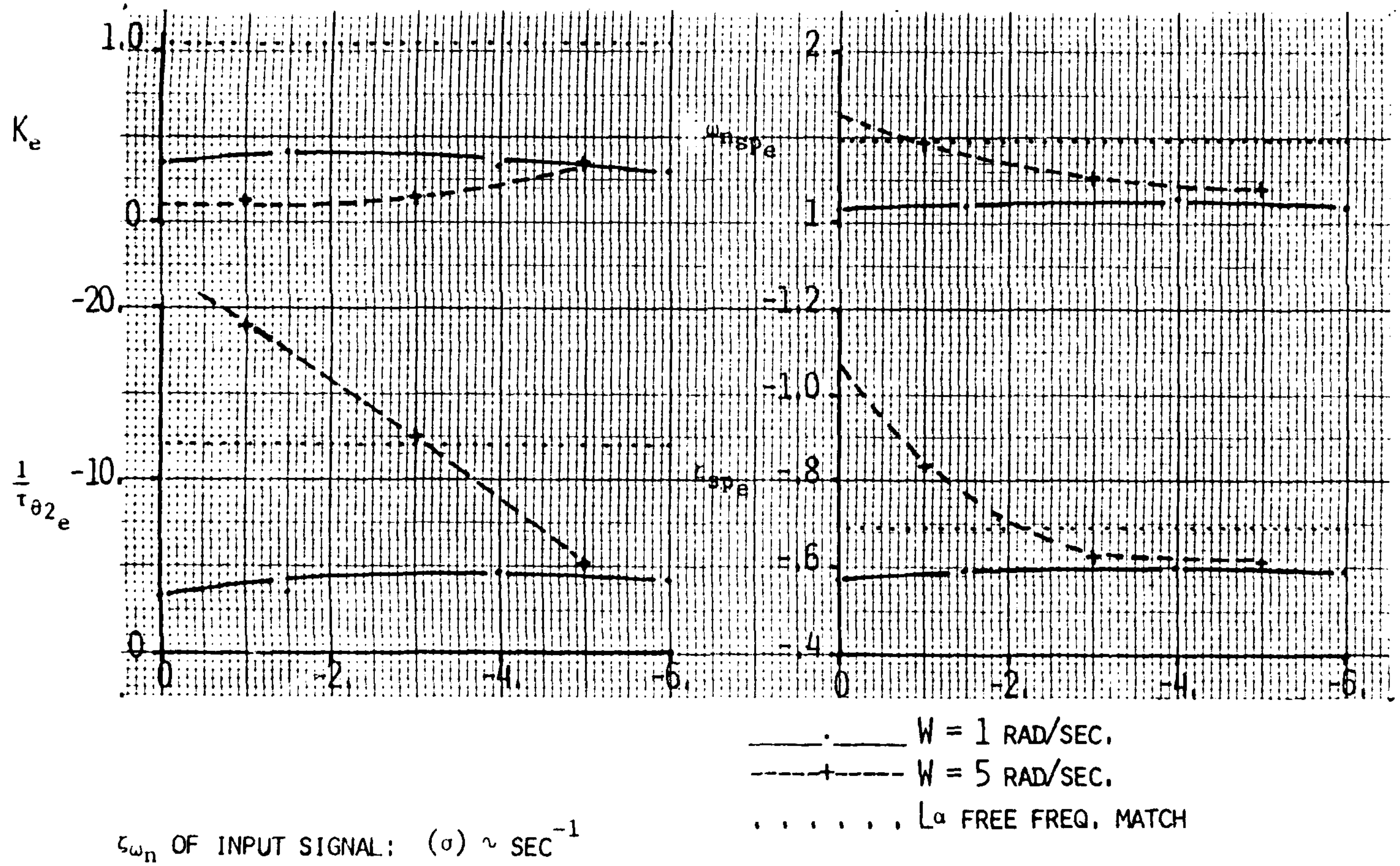


FIGURE 4.

Summary of Implications

The implications of time response matching make several strong statements about current methods which as yet have not been thoroughly verified by experiment. The method should be considered as an attempt to gain insight into the behavior of high order systems and evaluated in terms of its ability to account for observed trends in on going research efforts. The main implications of the method discussed in this paper are:

1. Equivalent systems is a valid concept.

2. Equivalent system parameters are functions of input.

   a. Frequency domain techniques may not always be reliable.

   b. Pilot rating may be a function of control technique.

3. Artificial time delays should not be used.

4. 1st/2nd order is the minimum acceptable form for lower order equivalents.

5. Failure to obtain a close frequency match is evidence that the equivalent system parameters may not be considered constant and is not sufficient reason to reject the system.

6. The pilot compensation model order in the Neal-Smith criterion should be increased for best results.

7. The high order system may be judged on the variation of equivalent system parameters over the pilot operating region.

References

1. Neal, T. P., and Smith, R. E., "An In Flight Investigation to Develop Control System Design Criteria for Fighter Airplanes," AFPDL TR-70-79, December 1970.

2. Smith, R. E., "Effects of Control System Dynamics on Fighter Approach and Landing Longitudinal Flying Qualities," Calspan Corporation Report No. AK-5280-F-12, March 1978.

Bibliography

1. Stifel, J. M., "A Time Response Approach to Equivalent Aircraft Dynamics," NADC-79231-60, October 1979.

2. Hodgkinson, J., Berger, R. L., Bear, R. L., "Analysis of High Order Aircraft/Flight Control System Dynamics Using an Equivalent Systems Approach," McDonnell Douglas Corporation Paper; MCAIR 76-007, April 1976.

3. Johnston, R. A., and Hodgkinson, J., "Flying Qualities Analysis of An In-Flight Simulation of High Order Control System Effects on Fighter Aircraft in Approach and Landing," McDonnell Douglas Corporation Report

ADVANCED FIGHTER TECHNOLOGY PROGRAM

Walter E. McNeill and Robert I. Sammonds

National Aeronautics and Space Administration

Ames Research Center

Moffett Field, California 94035

During the past 4 years, NASA has been engaged in a cooperative program with AFFDL to use Ames simulator facilities to study the application of advanced control modes to tactical aircraft. In this program, the area of application has been air-ground weapon delivery - specifically, the dive bombing task. The control modes considered for study were direct sideforce control (DSFC, mechanized to provide wings-level turn capability), direct lift control (DLC), and thrust/drag modulation (TDM) (fig. 1).

During the course of the program, DLC and TDM were studied only briefly, due to time constraints and limited apparent benefit to the dive-bombing maneuver. In the later simulation phases, which comprised two sessions in the Flight Simulator for Advanced Aircraft (FSAA), attention was focused on a detailed parametric study of the wings-level-turn (WLT) mode during dive bombing runs using a fixed, depressed-reticle sight and assuming delivery of unguided bombs. (Other studies had indicated that, of the proposed direct force modes, WLT showed the most promise as an aid in acquiring the target and making lateral corrections during the dive bombing task.).

Pilot input by means of the rudder pedals had been found during early studies to be the most natural method of applying direct sideforce. The WLT response of the delivery vehicle was assumed to be related to pedal input by the following transfer function:

$$\frac{a_{Y_{WLT}}}{\delta_p} = K_Y \cdot \frac{(T_1 s + 1)\, e^{-As}}{(T s + 1)\left(\frac{s^2}{\omega_n^2} + \frac{2\zeta}{\omega_n} s + 1\right)}$$

The gain, time constants, time delay, natural frequency, and damping ratio were subject to variation, singly or in combination, during the experiment. It was not the intention of the experimenters to simulate a particular design, only to provide an uncoupled (but realizable) WLT response with easily-variable characteristics.

Figure 2 shows the manner in which the WLT mode was mechanized for the purpose of the simulation. The sideforce coefficient $C_{Y_{WLT}}$ was fed directly into the airplane sideforce equation as the total C_Y. The compatible yaw rate r_{WLT} (equal to $a_{Y_{WLT}}/V_T$), modified by the proportional-plus-integral β feedback to ensure minimal sideslip, was introduced as the total body-axis yaw rate (by-passing the yawing equation) whenever the WLT mode was selected. The gain K_Y was adjusted so that a maximum of 3.0 G could be commanded during nearly the entire experiment. Because the maximum side acceleration capability of the FSAA was about 0.3 G, the machine could not approach the acceleration levels considered. However, normal flight and initial onset cues were provided.

Figure 3 depicts the dive bombing task. The initial altitude and release altitude were 10,000 feet and 5,000 feet, respectively. Because the FSAA visual system offered essentially only a straight-ahead field of view, a standard approach to a point abeam, pop-up, and roll-in to the target could not be used. Instead, an open-loop maneuver consisting of a 90-degree diving turn was adopted for initial target acquisition. Physical limits of the visual display system limited the dive angle to 30 degrees. The pilots were instructed to try to arrive at specified bomb-release conditions (airspeed, altitude, dive angle) simultaneously, and not to compensate for error in one variable by adjusting another. Scoring of impact error was not among the test data being gathered. To increase the piloting effort and exercise the WLT mode more fully, a change in aim to a secondary target (displaced 1000 feet laterally from the primary target) was commanded during roughly half the runs. This task was called the "coarse task". The task involving no target change was called the "fine task". The Cooper-Harper rating scale was used to rate the WLT response and ease of performing the tasks as the transfer function characteristics were varied. The results presented here are preliminary and subject to further analysis.

The natural frequency and damping ratio of the second-order part of the WLT response were varied from 0.5 to 12 rad/sec and from 0.3 to 2.0, respectively. Figure 4 shows variations of average pilot rating with natural frequency for the underdamped and critically-damped cases. Only data for the fine task are shown; the variations for the coarse task were similar but individual ratings were in general slightly less favorable. (There were no ratings worse than 7 because controllability was never in doubt.) In the middle frequency range ($3 \leq \omega_n \leq 8$) the best ratings were given to the $\zeta = 0.7$ cases. The data for $\zeta = 0.3$ and 0.5 show increasing degradation in ratings with respect to those for $\zeta = 0.7$ as frequency was increased, up to $\omega_n = 4.5$ rad/sec. The presence of overshoot in the response, by making lateral tracking of the target more difficult, may explain the poorer ratings. Looking only at the more highly-damped conditions in figure 4, it appears that a frequency of at least 4 to 5 rad/sec would be required for satisfactory characteristics.

Figure 5 shows pilot ratings for the overdamped cases vs. frequency expressed in terms of the value of the low-frequency real root. (For these cases, a spread of more than 5 to 1 existed in magnitude of the two real roots.) The critically-damped cases from figure 4 are repeated for comparsion. Plotted in this manner, the ratings for the overdamped cases fit generally in a narrow band as indicated by the shaded area. For these cases, the minimum negative real root value for satisfactory response appears to be about 3.

On the hypothesis that response bandwidth might serve as an overall correlating parameter, the rating data were plotted as functions of bandwidth (defined as the frequency at which the actual response fell 3 db below the zero-frequency level). These results are shown in figure 6. Smooth variations of average pilot rating with bandwidth were obtained for $\zeta = 0.7$ and greater, but distinct variations for each value of ζ are seen, indicating a still-separate effect of damping ratio. Here, the highest (overdamped) cases received the best ratings for a given bandwidth. Curves plotted for $\zeta = 0.3$ and 0.5 deviate in the unfavorable direction from the trends shown by the higher-damping data, indicating again the degrading effect of overshoot in the WLT response.

Figure 7 shows the effect of variation of the pure time delay generated by e^{-As}, starting with the base condition $\omega_n = 15$ and $\zeta = 1.4$. As expected, deterioration in rating occurred for both fine and coarse tasks; however, the coarse task tended to be rated worse because of the increased anticipation required to stop the turn precisely on target. This requirement apparently was more troublesome than the effect on fine tracking. These data indicate that for the purpose of establishing a maximum allowable delay, as might be introduced by a digital flight control system, one should pick a value somewhere around 0.1 second.

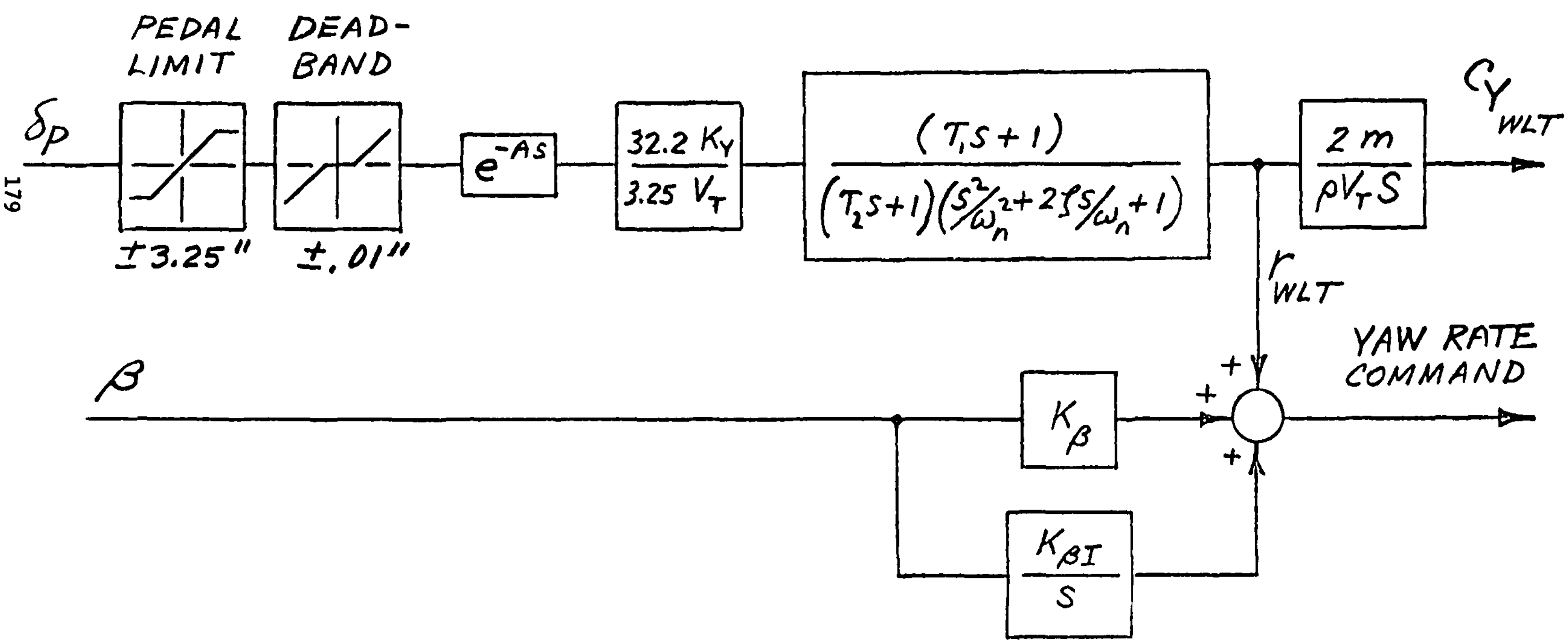
The amounts of WLT sideforce authority actually used during typical coarse-task runs are indicated in figure 8. Three levels of maximum authority (commanded side acceleration available, proportional to pedal deflection) were provided: 0.5, 0.75 and 3.0 G. Each curve is a distribution function which indicates, for any given percentage of run time, that the commanded side acceleration was equal to or less than a certain value. The curve for 3.0 G indicates that approximately 1 G capability would suffice for 75 percent of the time and therefore might serve as a reasonable minimum requirement. The lowest level of authority (0.5 G) was inadequate for the task. Pilot comments indicated that even during the fine task target acquisition and tracking with this limited authority was very difficult if not impossible, so it appears that the change to the secondary target was not seriously attempted during the coarse task.

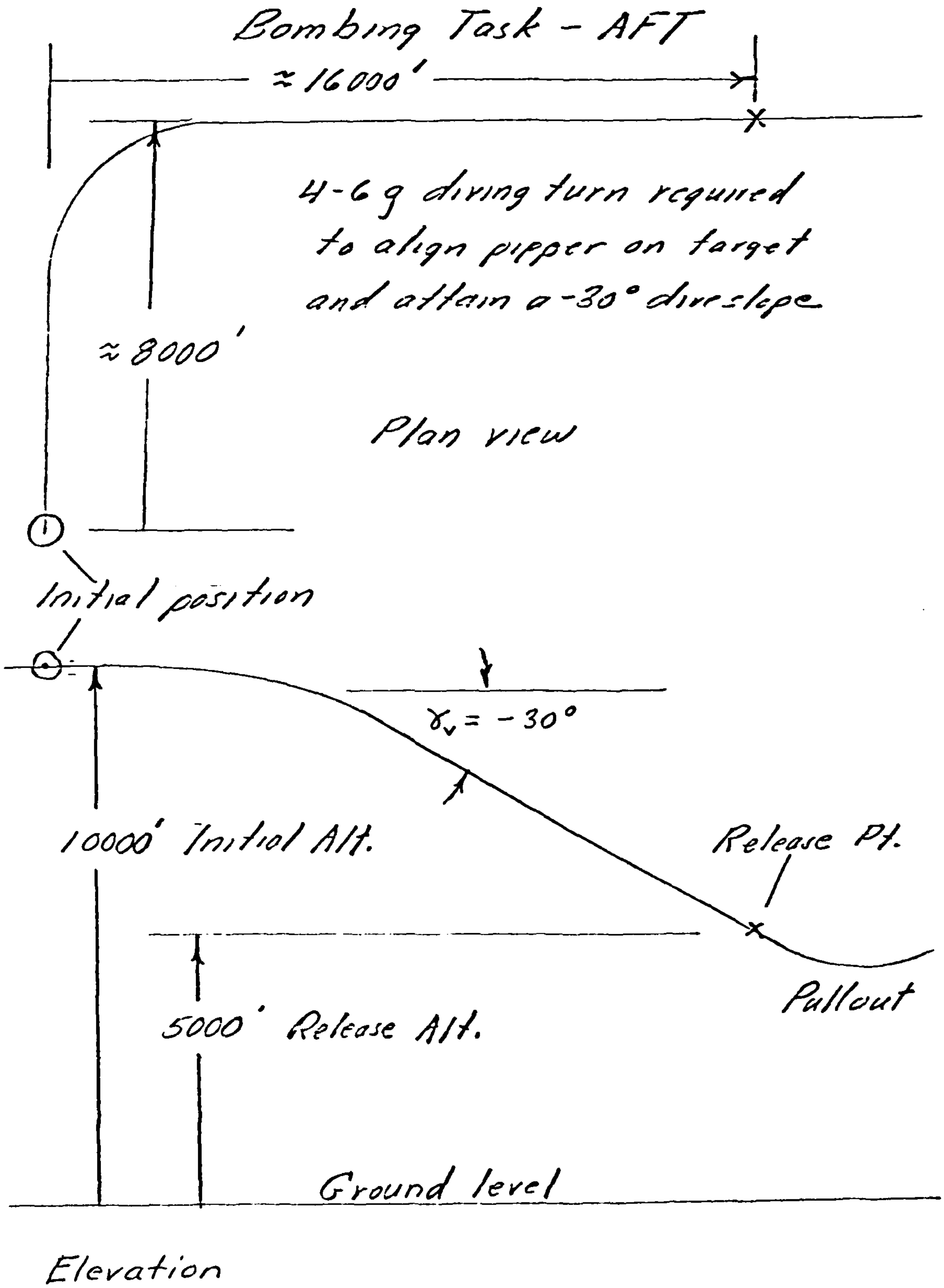
Figure 9 summarizes some of the tentative conclusions of the Advanced Fighter Technology program as of the date of the present Symposium and Workshop. The preliminary nature of the results is again emphasized. A NASA Technical Publication covering this work and authored by Robert I. Sammonds (NASA/Ames) and John W. Bunnell, Jr. (Capt., USAF/AFFDL) is now in preparation.

AFT PROGRAM

- JOINT NASA - AFFDL PROGRAM
- EVALUATION OF ADVANCED CONTROL MODES FOR AN AIR-GROUND WEAPON-DELIVERY TASK
  - WINGS-LEVEL TURN (WLT)
  - DIRECT LIFT CONTROL
  - THRUST/DRAG MODULATION
- FINAL SIMULATION PHASE
  - PARAMETRIC EVALUATION OF WLT RESPONSE VARIABLES

WLT MECHANIZATION



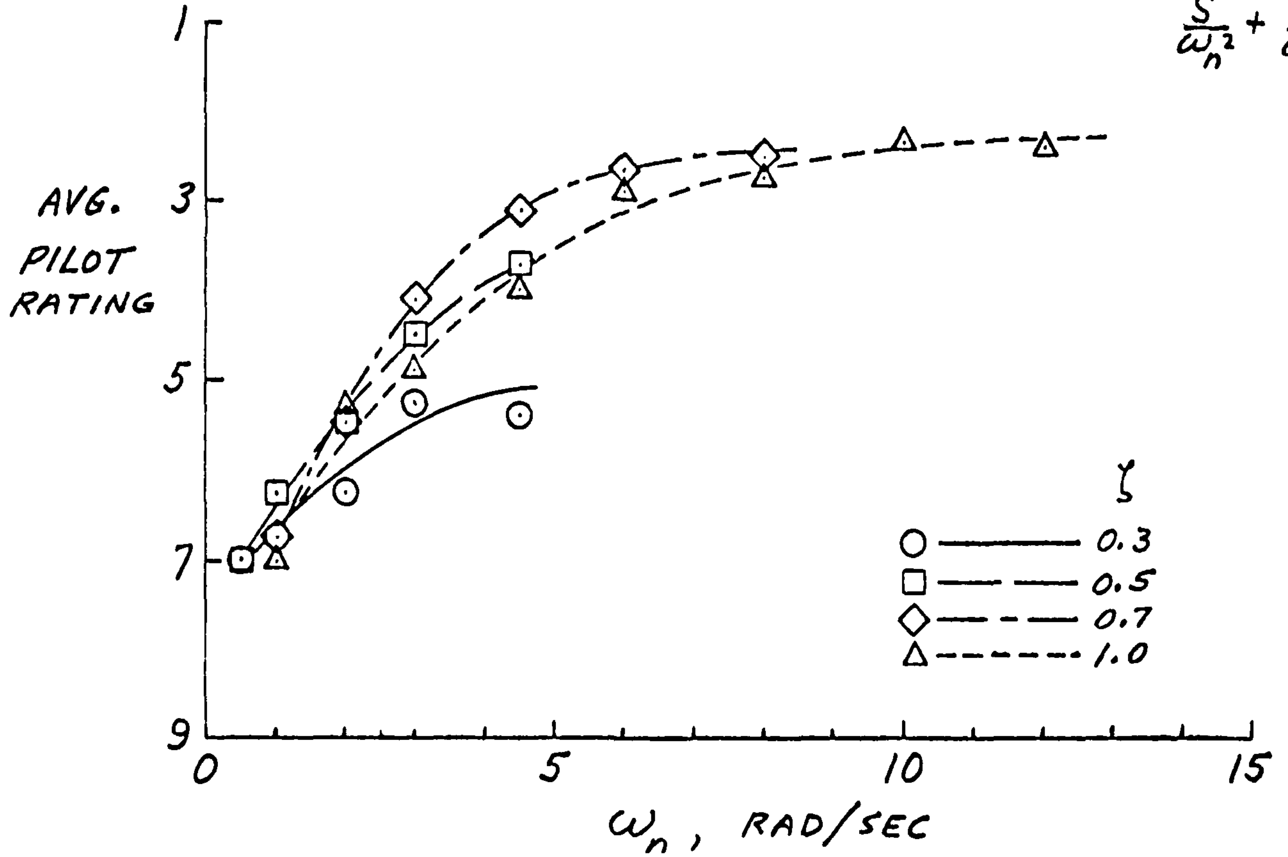

Bombing Task - AFT
≈ 16000'
4-6 g diving turn required
to align pipper on target
and attain a -30° diveslope
≈ 8000'
Plan view
Initial position
$\gamma_v = -30°$
10000' Initial Alt.
Release Pt.
Pullout
5000' Release Alt.
Ground level
Elevation

RATING VS. NATURAL FREQUENCY

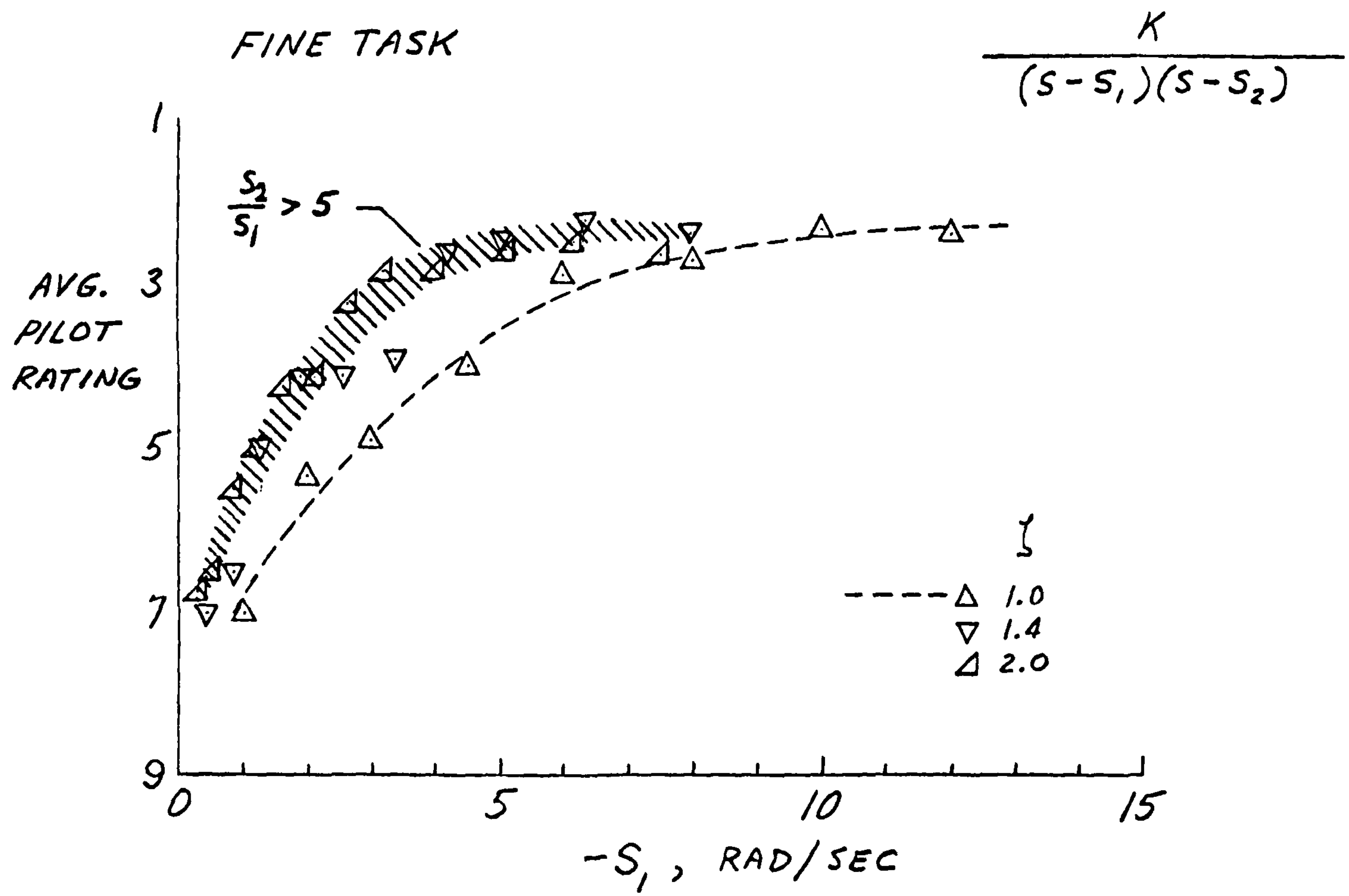
FINE TASK

AVERAGE OF 2 PILOTS

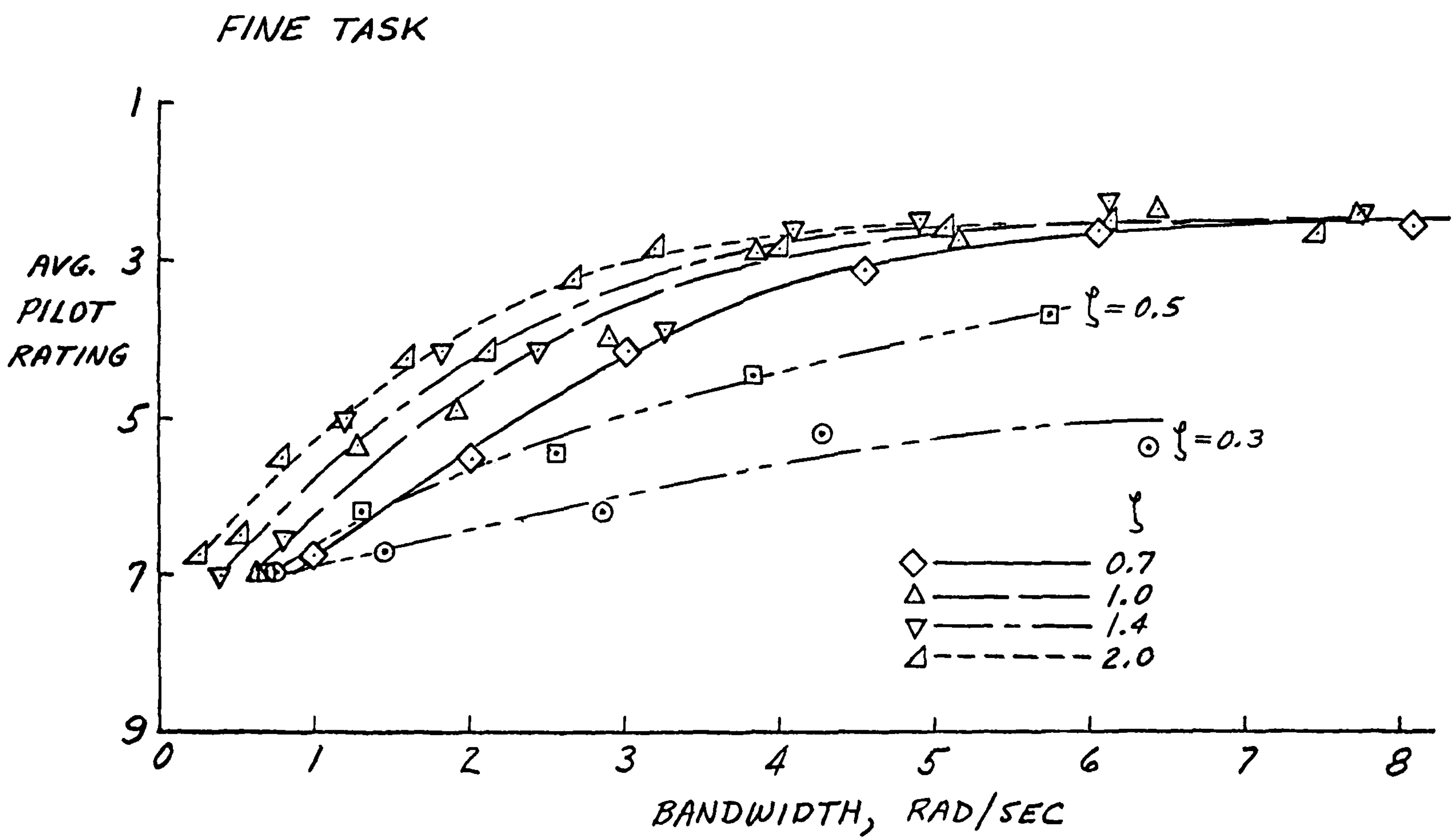
$$\frac{K}{\frac{S^2}{\omega_n^2} + \frac{2\zeta}{\omega_n} S + 1}$$



RATING VS. LOW FREQUENCY ROOT

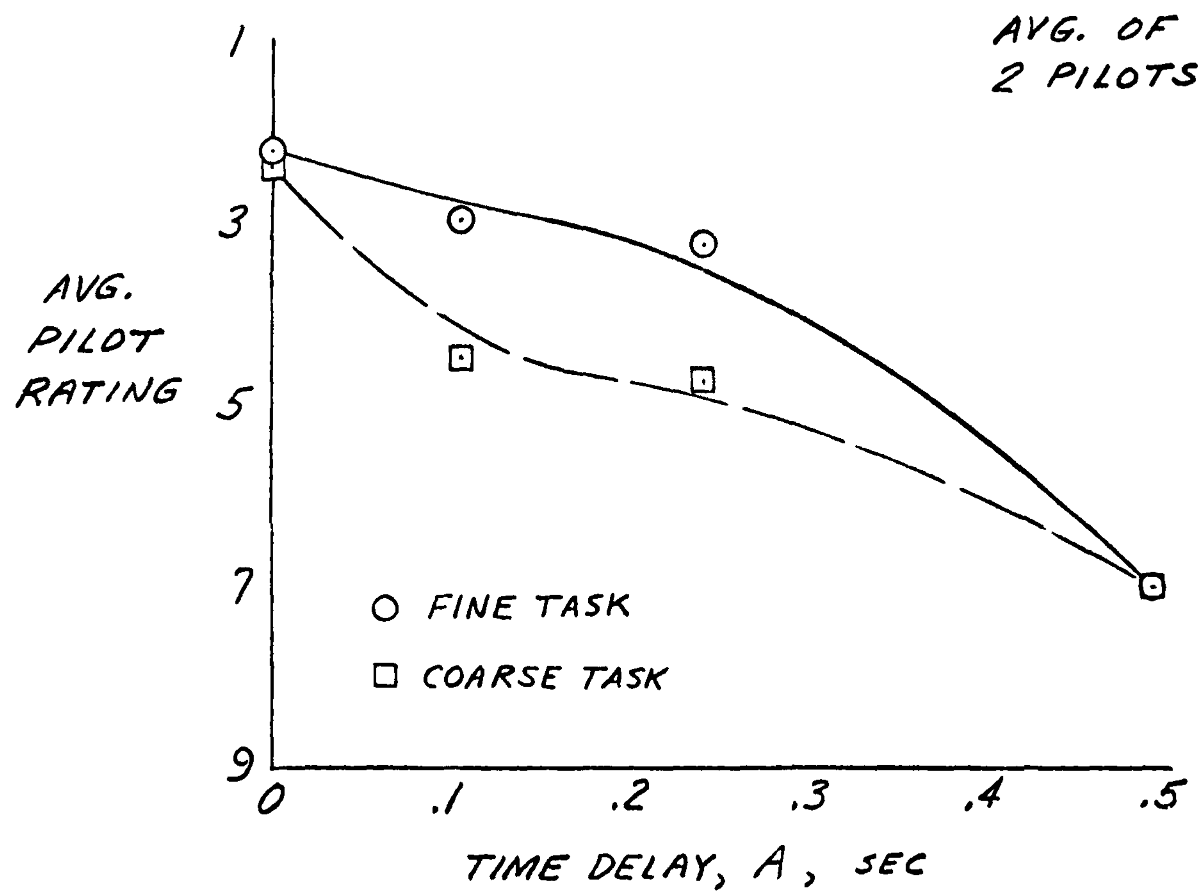


RATING VS. BANDWIDTH

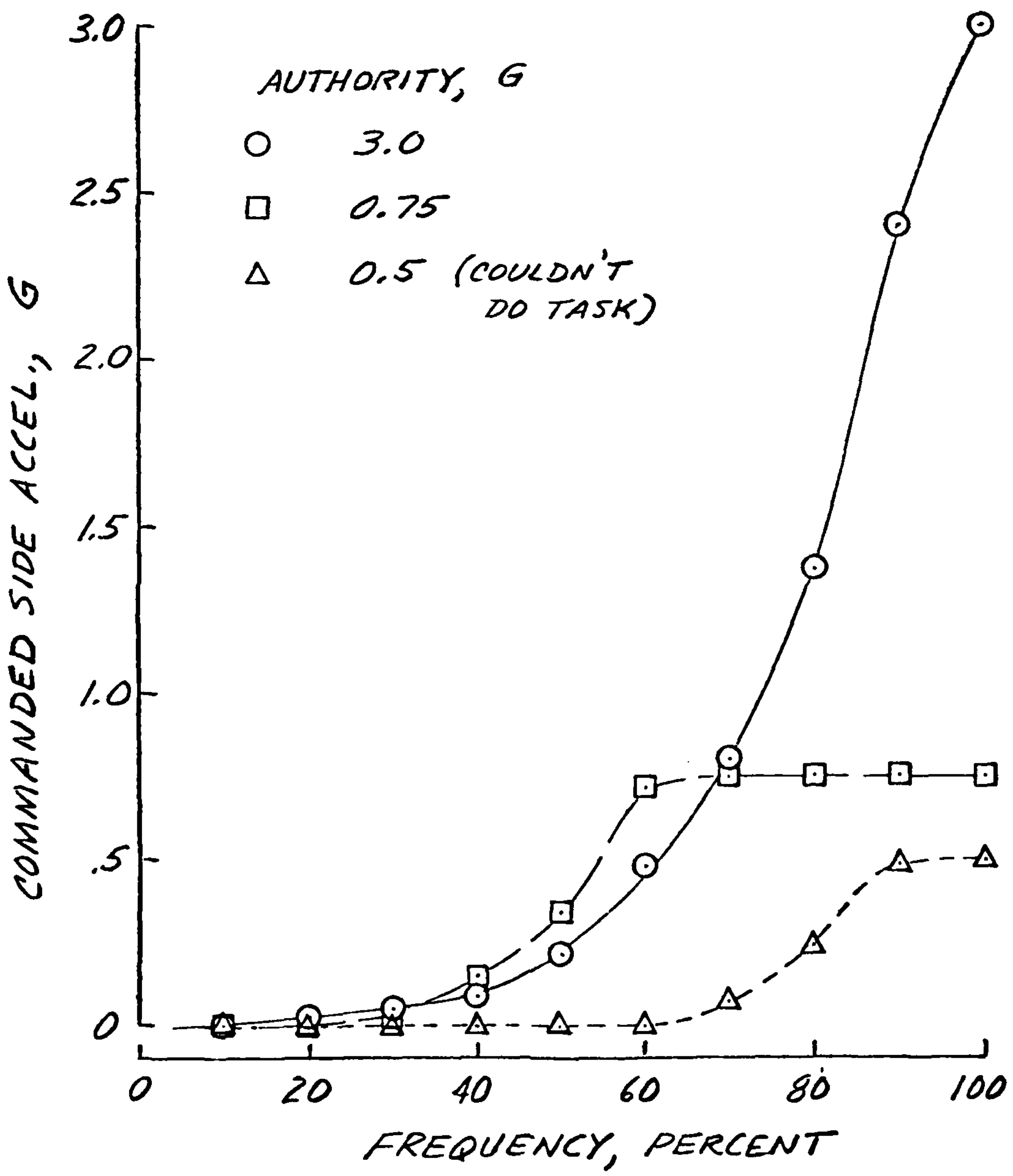


EFFECT OF TIME DELAY

e^{-As}



WLT AUTHORITY USAGE



SUMMARY

- WLT MODE USEFUL IN DECREASING WORK LOAD FOR DIVE BOMBING WITH FIXED, DEPRESSED SIGHT
- PREFERRED CHARACTERISTICS FOR SATISFACTORY SYSTEM:
  - BANDWIDTH GREATER THAN 3 RAD/SEC
  - CRITICAL DAMPING
  - 1.0 G AUTHORITY REQUIRED

DISCUSSION ON 10 OCTOBER 1979 PRESENTATION BY

WALTER McNEILL

WINGS LEVEL TURN SIMULATOR EVALUATION

(Question: To what level of lateral acceleration can the human pilot be expected to function suitably?)

Jack McAllister, GENERAL DYNAMICS:

There were two noteworthy occurrences on the Fighter CCV Program that give some indication of the allowable lateral acceleration level for the human pilot. In both instances an automatic disconnect from Direct Sideforce operation occurred at about 0.9 g lateral acceleration. In the first occurrence, the pilot was intentionally exercising the automatic disconnect feature and the ensuing response was considered to be mild. In the second occurrence, a different pilot experienced a gust induced automatic disconnect from a full A_y mode steady-state command. This second occurrence resulted in some unintentional pilot-aircraft coupling and was considered to be the maximum transient comfortably tolerable. Aside from the unexpected transients, operation at lateral accelerations up to 0.8 g was considered satisfactory although reaching laterally to locate and activate a switch, etc., while at these lateral acceleration levels was quite difficult.

SECTION III

WORKSHOP DISCUSSIONS

WORKING SESSION

CLOSED LOOP CRITERIA

MODERATOR: Frank L. George

Flight Dynamics Laboratory

This session focused on discussion of three informal papers presented by Larry Taylor of NASA Langley Research Center, Dr. David Schmidt of Purdue University and Ed Onstott of Northrop. The intent of having these papers presented was to evoke discussion of three topics pertinent to closed loop flying qualities criteria. These topics were analysis and techniques, metrics and criteria definition.

Abstracts of the presentations by Mr. Taylor and Dr. Schmidt are included here. Mr. Taylor's presentation consisted of first results of some work in progress and it is suggested that those who are interested in further details contact him directly. Further details of Dr. Schmidt's presentation may be found in his AIAA paper (79-1749) from the 1979 AIAA Guidance and Control Conference, or in the AIAA Journal of Guidance and Control. The complete text of Mr. Onstott's presentation is printed here.

Both Taylor's and Schmidt's presentations rely on the multivariable capability of optimal control theory to formulate the pilot-in-the-loop control problem, and the quadratic performance index as a means of quantifying the closed loop system performance. Both see the performance index as a link between the quantitative system performance measures and the traditional pilot subjective assessment of system characteristics, the Cooper-Harper Rating. Others, Dr. Ronald Hess at NASA Ames for example, have also investigated this relationship. Onstott's paper deals more generally with the philosophy of defining flying qualities criteria in the context of the intended mission or application of the aircraft. Several important considerations involved with this approach to defining criteria are discussed, such as the need to present specific flying qualities requirements as design goals without constraining the design methods or technology applications. The presentations stimulated much comment and discussion. While no major conclusions were reached, there seemed to be general endorsement of pursuing more analytical approaches to developing and defining flying qualities criteria.

DESIGN CRITERIA SUITABLE FOR OPTIMAL FLIGHT CONTROL
WHICH RELATE TO PILOT RATINGS

By Lawrence Taylor

NASA Langley Research Center
Hampton, VA 23665

ABSTRACT

Design criteria suitable for applying linear, quadratic, Gaussian modern control synthesis to the flight control problem, are developed which relate to (1) pilot ratings of the augmented handling qualities, (2) subjective ratings of aircraft response to turbulence, (3) limit cycles, (4) high order system response, and (5) simultaneous consideration of diverse flight and loading conditions. The criteria are based on an integral quadratic cost function which penalizes the difference between the desired response and the actual response for a set of design points (see Figure 1). The desired response and turbulence input are modeled as the output of separate systems subjected to white noise. The total problem, although complex, is amenable to optimization using modern control theory.

The advantage of the criteria discussed lies in its integration of many of the numerous aspects of designing flight control systems (see Figure 2). The relation of the criteria to pilot rating is not as strong as one might like, particularly to pilot-induced-oscillation situations. Much work remains before the approach taken can become part of a flying qualities design criteria, but the potential benefits justify continued research.

TOTAL SYSTEM BLOCK DIAGRAM

(WITH PILOT FEEDBACK)

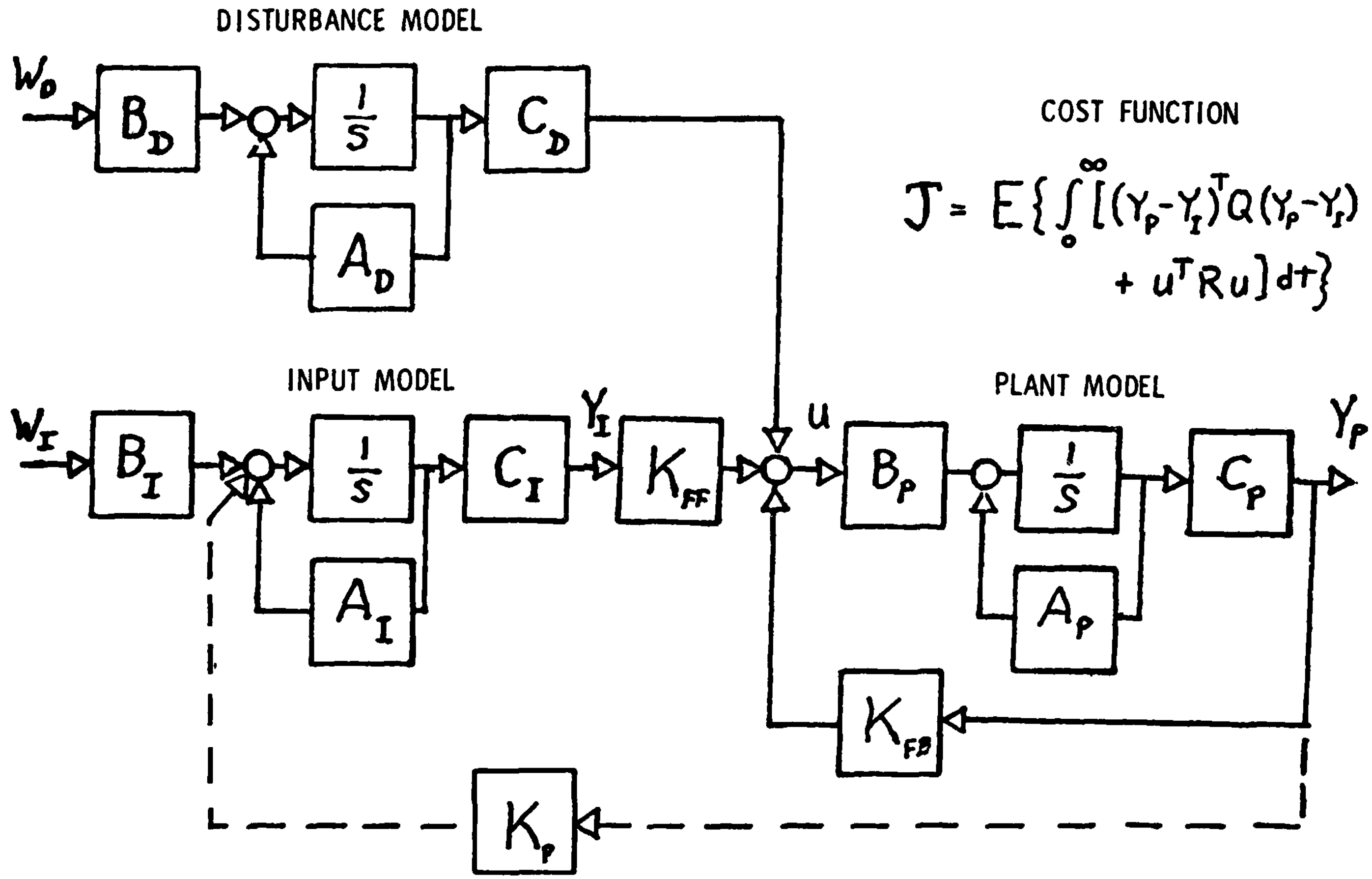


FIGURE 1 CLOSED LOOP CRITERIA MODEL

DOES QUADRATIC PERFORMANCE INDEX CONSIDER ADEQUATELY:

FLYING QUALITIES DESIGN CONSIDERATIONS	
STABILITY	YES
DAMPING	YES
RESPONSIVENESS	YES
MANEUVERABILITY	YES
CONTROLLER CHARACTERISTICS	?
COUPLING	NO
HIGH ORDER	YES
RESPONSE TO TURBULENCE	YES
NONLINEAR EFFECTS	?
VARIOUS FLIGHT/LOADING/FAULT CONDITIONS	YES
MISSION REQUIREMENTS	?
AIRCRAFT TYPE	?
WORK LOAD	?

FIGURE 2 RELATIONSHIP BETWEEN QUADRATIC PERFORMANCE INDEX AND DESIGN CONSIDERATIONS

PILOT-OPTIMAL AUGMENTATION
FOR THE AIR-TO-AIR TRACKING TASK

David K. Schmidt
Purdue University
West Lafayette, Indiana

Abstract

A method based on optimal control techniques, closed-loop task-oriented design objectives, and an optimal control model of the human pilot (see Figure 1) was applied to augment the system dynamics in a longitudinal air-to-air tracking task. The plant dynamics included not only the vehicle short period mode but the dynamics of two different lead-computing sight displays, at different tracking ranges and levels of target acceleration. Previously obtained experimental results were duplicated, a family of full-state feedback linear control laws developed, tracking improvements predicted, and augmented system dynamics (eigenvalues) investigated. The results demonstrate the dependence of the desirable vehicle (short period) dynamics on the dynamics of the other system modes (e.g., the display), thus emphasizing the importance of con idering all the system dynamics in handling qualities investigation and stability augmentation synthesis (see Figure 2).

INTEGRATED MANUAL AND
AUTOMATIC CONTROL
<u>OF COMPLEX FLIGHT SYSTEMS</u>

High-Order Systems	→	Optimal Multi-variable Control Theory
Compatible with Human Pilot Limitations	→	Coupled Automatic Synthesis with Optimal Control Pilot Model
Maximizes Human Pilot Acceptance (rating)	→	Invokes the Hypothesis of Objective Function/Pilot Rating Correlation

FIGURE 1 RATIONALE FOR METHOD

DIRECTOR SIGHT DISPLAY σa_T = 5 g's, D = 1000 ft.	Unaug.	Level A	B	C
Tracking error, ε (deg)	1.92	1.71	0.95	0.35
Stick Defl., δ_{st} (deg)	3.61	3.55	3.50	3.55
Stick Rate, $\dot{\delta}_{st}$ (0/sec)	7.16	6.25	5.39	4.97
Elev. Activity, δ_E (deg)	2.86	2.85	2.81	2.79

LCOS SIGHT DISPLAY	Unaug	Level A	B	C
Tracking Error, ε (deg)	3.05	2.53	1.35	0.74
Stick Defl., δ_{st} (deg.)	3.71	3.74	4.21	7.38
Stick Rate $\dot{\delta}_{st}$ (0/sec)	7.33	6.81	6.57	11.18
Elevator Act., δ_E (deg)	2.96	2.91	2.84	2.81

FIGURE 2 EFFECT OF SIGHT ON TRACKING ERROR

AN ECLECTIC REFORMULATION OF FLYING QUALITIES

E. D. Onstott
W. H. Faulkner

Northrop Corporation
Aircraft Group
Hawthorne, California

ABSTRACT

The development of high authority and non-standard control configurations has led to aircraft designs that cannot be well correlated with the existing flying qualities data base. For the subject of flying qualities to be responsive to current needs in aircraft design and procurement, an eclectic reformulation of the subject is required. This paper presents one approach that allows much greater freedom in problem formulation and suggests ways to free the subject area from the domination of specialized methodologies.

INTRODUCTION

The authors have recently completed a study for the USAF Flight Dynamics Laboratory which resulted in the documentation of a comprehensive account of one particular approach to the prediction, evaluation, and specification of flying qualities. This time history simulation technique was not intended to replace or render obsolete other flying qualities approaches; rather it was initially developed to analyze problems that were not amenable to study by linear or time-invariant means. Since the publication of the contract report, AFFDL-TR-78-3, the authors have received a number of comments that indicate two widespread difficulties:

- The subject of flying qualities is often defined by its practitioners in terms of existing analytical and test methods.
- It is difficult for new approaches to the subject to be properly understood in relation to the existing technology.

It is the object of this paper to indicate how the subject of flying qualities inherently contains the means to overcome the limitations of established methodologies so that a fully eclectic capability will be available for the study of aircraft now being designed. Two things will be presented:

- A discussion of how flying qualities can be defined with respect to its functions: evaluation, specification, and prediction.
- An indication of how the definitions and subject requirements of flying qualities can be interpreted in terms of specific methods of testing, specification, analysis, and prediction.

Conventional flying qualities practice implicitly depends on the almost universal dynamic similarities of fixed-wing aircraft. This allows a direct comparison of air-frame dynamics that are easily calculated and correlated with operational experience. However, the recent development of high authority control systems which tend to obscure the basic airframe dynamics implies that the conventional aircraft comparisons are no longer sufficient as the basis of flying qualities analysis.

Furthermore, the domain of flight controls and flying qualities is becoming considerably broader as a result of:

- Integration of control, propulsion, weapons, and navigation systems.
- Ability to decouple and regroup the aircraft dynamic modes.
- Advanced head-up and CRT displays.
- New controller concepts.

For these reasons, experience based on aircraft comparisons cannot constitute a complete basis of flying qualities work in future applications. Thus, to be responsive to the needs of aircraft design and procurement, the subject of flying qualities must be reformulated in accordance with the following postulate:

<u>All flying qualities evaluation, specification, and prediction concerns must be expressed in terms of a particular airplane and how well it can meet intended design and procurement objectives.</u>

The practice of flying qualities has started adopting this basic postulate in the following areas:

- Flight test and simulation — development of standardized test maneuvers, Reference 1.
- Specification — proposed USAF Prime Standard and Handbook, Reference 2.
- Analysis and Prediction Methods — CCV studies, target tracking analysis, discrete maneuver analysis, Reference 3.

These trends reflect the importance of asking the right questions in terms of what the pilot can make the airplane do, independent of established analysis methodologies.

In order to see how the basic postulate can be followed, it will be useful to examine the resources of flying qualities as a subject and how they can be used for the principal applications of flying qualities evaluation, specification, and prediction for each area of concern.

DEFINITION OF FLYING QUALITIES

Historically, the subject of flying qualities has developed by utilizing available analytical and experimental methods. These constitute the subject's four basic resources:

- Historical data and data correlations.
- Flight test procedures and capabilities.
- Flight simulation methods, both in-flight and ground-based.
- Mathematical modeling and analysis techniques.

For example, the description of aircraft dynamics, both open and closed loop, has followed the trends of control theory. Frequency response descriptions were first employed, but with the development of root locus methods, eigenvalue descriptions became widely used. At present, state variable and optimal control methods are becoming prominent along with time history simulations. At each stage of this development, there were increased capabilities to correlate aircraft dynamics descriptors, and to define further aspects of flying qualities consideration in terms of available dynamic models. In this way, the available or accepted methodologies determined what aspects of piloted flight were appropriate for study.

If flying qualities is to become fully responsive to advanced aircraft design and procurement, this process must be reversed. By investigating definitions and objectives of the subject, guidelines for the supporting methodologies can be established; the following discussion will do just this.

In developing the subject independent of methods, it should be kept in mind that there are a large number of dynamic aspects of piloted flight that are largely independent in description. This diversity includes, for example,

open loop response	display and cockpit layout
precision tracking	flight safety
PIO	formation flight
integrated fire-flight control	feel system characteristics

and the investigation of a particular aircraft must include all such relevant items of concern.

In terms of the above considerations, the subject of flying qualities can be defined as the discipline of investigating all relevant areas of concern by means of the above resources for the following purposes:

- Judging the performance of a specific airplane.
- Aircraft procurement and design specification.
- Aircraft performance and flying qualities prediction for use in:
  - Aircraft design and development.
  - Aircraft improvement and modification.

AIRCRAFT EVALUATION

Before judgments can be made concerning piloted performance, data must be obtained from, or assigned to, the airplane under consideration. This process of obtaining descriptive piloted performance data is called aircraft evaluation and data obtained can be classified as follows:

- Objective - numerical measures obtained through instrumentation.
- Subjective - pilot statements.
- Analytical - behavior of mathematical aircraft dynamic models.

The totality of these evaluation data for a given airplane is called its flying qualities, while the totality of the subjective evaluation data is often referred to as the handling qualities.

Objective Evaluation Data

Objective data can be routinely obtained for all aspects of aircraft performance. Consequently, there is no restriction in applying the basic postulate of flying qualities with respect to aircraft evaluation using objective data.

Subjective Evaluation Data

The pilot's subjective evaluation consists of how well he thinks the airplane did or could do, and how much "workload" was involved, supported by diagnostic comments about good or deficient airplane characteristics. This information can be obtained from the pilot for each area of concern, or as a summary of particular aircraft flight or mission phases. This subjective evaluation is always available in conjunction with any flight test item that leads to objective evaluations.

Although there are two possibly independent aspects in the pilot's evaluation, performance and workload, there has been a highly successful and almost universal method of reducing the subjective evaluation to a scalar quantity, namely the pilot opinion rating, Reference 4. Since pilot acceptance of an airplane is of great importance along with acceptable objective performance, the use of pilot opinion rating methods, particularly the Cooper Harper rating scale, should be continued.

Unfortunately, there has been no standard method for supporting the rating by diagnostic comments. This means that it is seldom possible to understand the blend or compromise of performance and "workload" that a pilot has used in giving his rating judgement, even though a decision tree of performance and compensation descriptors is explicitly provided in the Cooper Harper rating method. This is further confused by diverse assumptions adopted by many flying qualities analysts that workload is:

- compensation
- identified pilot parameters
- physical exertion against controller force gradients
- reserve attention
- time estimation
- total angular rate
- pilot - aircraft payoff functional

Depending on the flight task evaluated, each of the above interpretations of workload may be the most meaningful or influential on the pilot rating. In the case of an airplane with a high workload, it is important to understand the exact dynamic nature of the problem before corrections to aerodynamics or control modifications can be undertaken. For these reasons, it is recommended that in support of a Cooper Harper pilot rating, the pilot state what aspects of workload seem to dominate. This should be included in a standardized diagnostic questionnaire. This recommendation implies no change in the Cooper Harper rating scale or methods; it applies exclusively to the way and precision with which the scale is employed.

Analytical Evaluation Data

Analysis as a means of aircraft evaluation must be carefully understood. As an evaluation, any performance measure obtained by analysis must be regarded as equivalent to what would be measured using the actual airplane. Thus a valid analytical evaluation has the same evaluation status as actual flight test data. Examples allowed by Air Force specification practice include dutch roll and short period eigenvalues calculated from determined airframe aerodynamics, and dutch roll mode amplitude and phase measures also calculated from aerodynamic data. In this way, the calculated eigenvalues, for example, are used to determine acceptable or unacceptable performance according to Reference 5, Military Specification, Flying Qualities of Piloted Airplanes, MIL-F-8785B.

For this reason, analysis methods must be far more reliable than prediction methods, whose main purpose is to guide early design and development. In order to assure the required reliability, the following conditions on the analytical methods should be met whenever possible:

- All calculated quantities should be potentially measurable or reducible from flight test data.
- Verifications by flight test data should be obtained for representative flight conditions.
- All data used in the calculation must be either obtained from, or verified by, flight testing.
- All aircraft, control, and aerodynamic models, regardless of formulation in the time domain, s-plane, or state space, must be sufficiently general to include all relevant dynamic and kinematic effects.

It was stated in the Introduction that the basic postulate of flying qualities implied that questions concerning a particular airplane should be phrased in terms of its particular design and procurement objectives. This means that to be most meaningful, the following three questions must be resolved prior to flight testing and analysis:

- What test maneuvers are to be flown?
- Which items are to be evaluated by the same test maneuver?
- For what purposes are the objective and subjective data to be used?

AIRCRAFT SPECIFICATION

Specification consists of criteria by which judgments are assigned to aircraft evaluation data. These come about in the following way: Procurement objectives state what the intended airplane must be able to do, while specification criteria, whether developed by the procuring agency or the airplane designer, express how well the airplane should perform in terms of aircraft evaluation and pilot acceptance as discussed above. The overall objectives of satisfying the specification criteria are:

- guaranteed aircraft capability
- guaranteed pilot acceptance

Procurement criteria, such as MIL-F-8785B, have evolved by identifying correlations among conventional aircraft between performance measures and acceptable pilot ratings. In this way, the evolved criteria have dictated the performance measures to be evaluated along with associated flight test and analysis methods. Since this approach requires comparison of many similar aircraft, specification methods must be substantially augmented for current and future specification of unconventional new designs and mission roles.

On the other hand, if evaluation measures have been comprehensively developed for a particular airplane in accordance with the basic postulate, then all that is required are decisions on how well the airplane should perform on each objective and subjective evaluation item. In this way, the most meaningful evaluation of a particular airplane dictates an appropriate specification with respect to the procurement and design objectives.

Introduction by the United States Air Force of the USAF Prime Standard and Handbook to supersede MIL-F-8785B, Reference 2, will achieve the above objective supported by the data base of the current specification and its background and user guide, Reference 6. The large number of independent evaluation items will require a widely diverse supporting technology. This must be well represented in the new documents which will indicate many ways to approach evaluation and specification.

It should be noted that the flying qualities analysis of future aircraft performed in accordance with the principles outlined above, will proceed by selecting the most appropriate and comprehensive objective and subjective evaluation items, placing specification requirements on them, and only then, selecting analysis and prediction methods to support the design and development of the airplane. It was pointed out above that prediction and analysis methods are used in entirely different ways; this will next be considered in more detail.

PERFORMANCE AND FLYING QUALITIES PREDICTION

Prediction of flying qualities consists of developing and exercising mathematical models of open loop and closed loop aircraft response. The objectives of these analyses are to:

- Predict compliance of evaluation items with specification criteria.
- Predict probable performance, pilot acceptance, and dynamic characteristics.
- Predict performance tradeoffs among design parameters.

Inasmuch as future aircraft evaluations and specification criteria will be generated according to design and procurement objectives, many new kinds of prediction methods must be developed and validated. These methods must predict both objective and subjective evaluation data for all areas of flying qualities concern. In this way, the selection of evaluation parameters and specification criteria will lead to selection of the appropriate pilot - aircraft models and prediction techniques. This resulting prediction methodology will be useful in the following ways:

- To guide preliminary aerodynamic and control design.
- To guide final design during aircraft development.
- To identify, understand, and eliminate flying qualities deficiencies.
- To assist in demonstrating compliance with procurement and design objectives.
- To assist in interpretation of pilot ratings and comments.
- To search for and identify unrecognized but relevant flying qualities phenomena.

The selection of appropriate prediction methods depends upon the representation of a particular item of flying qualities concern. This representation will always consist of three separate parts. They are:

- Task Model. This is a mathematical description of a sufficiently representative flight test item.
- Aircraft or Pilot - Aircraft Model. These models represent the dynamics of the airplane or the closed loop piloted response during the performance of the task as represented by the task model.

- Evaluation Model. The evaluation model should include all objective evaluation items that would be obtained during the corresponding flight test. The evaluation must also include data which can be shown to correlate well with subjective pilot ratings and comments.

Once these model components have been chosen, the particular techniques for calculating the evaluation quantites can then be selected or developed.

Task Model

Task model selection in addition to being required for prediction methods, is also an important aspect of flight test programs. For example, Twisdale, Neal and Smith, and Meeker and Hall, References 1, 7, 8, have performed extensive flight test and in-flight simulation studies using target tracking during wind-up turns, attitude tracking of random commands, and step attitude tracking. These task models were selected to be representative of combat tracking, and have proved to be good predictors of aircraft operational experience. The success of these models makes them likely candidates for use in the prediction of combat tracking by means of closed loop pilot - aircraft modeling methods.

Aircraft Model

Aircraft model selection depends on the task model in the following ways:

- Flight condition. High angle of attack or sideslip angles may require nonlinear aerodynamic data.
- Maneuvering required. Large angular excursions and high angular rates may require nonlinear coupled equations to represent adequately the performance of the task model.
- Control system characteristics. If the performance of the task model results in limiting of rates or control surface excursions, these effects must be included in the model. Other dynamic effects such as control augmentation saturation must also be included.

It should be noted that the selection of an appropriate model does not necessarily imply the selection of a computational method, but determines only the necessary dynamic capabilities a computational context for the problem must possess.

The principal uses for the aircraft model are:

- Open loop aircraft analysis.
- Closed loop aircraft analysis.
- Use of the aircraft model for manned flight simulation.

Flight simulation is a reliable method for predicting both objectives and subjective evaluation data. However, the reliability of these predictions depends heavily on such factors as airplane model fidelity, visual and motion cue fidelity, and computational efficiency in both ground-based and in-flight simulations.

Pilot — Aircraft Model

Pilot - aircraft model selection depends on both the task model and the relevant evaluation items. The aircraft part of the pilot - aircraft model should be chosen as above, and the pilot model must be expressed in whatever computational context this requires. Unfortunately, the use of pilot models in flying qualities analysis has remained controversial and non-standardized for the following reasons:

- The pilot model has usually dictated a strictly linear and time-invariant problem formulation.
- The pilot model is often not well defined in terms of what model components are to be used, what dynamic limitations apply, and what adjustment or optimization rules are to be followed.
- The calculation methods are often obscure and the data from the model difficult to compare with flight test or simulation results.

Recent extensions, Reference 3, in pilot model theory have eliminated the linear and time-invariant restrictions, and models can now be chosen to fit any computational context required by the problem formulation. More precisely, all currently used models are special cases of the following definition which will be adhered to in the subsequent analysis:

Definition: A pilot model is a rule that assigns a dynamical description of a pilot's activity during a given task along with a method for using the model to predict evaluation data. This dynamical description is subject to human limitations that include:

- transport time delay
- human visual resolution and motion perception thresholds
- limited motor information output channels
- neuromuscular dynamics effects

For precision control tasks, the model is adjusted to produce optimum performance with respect to the evaluation parameters. This adjustment may incorporate time-varying compensation, attention allocation, discrete control inputs, and other control strategies that can be identified in human pilot activity.

The selection of a particular set of pilot model characteristics should be made exclusively on the basis of relevant pilot activity for each flying qualities evaluation task item. This implies that the model must be developed independent of computational method, and that various models and computational methods might be required in the study of any given airplane.

Evaluation Model

The evaluation model consists of a set of performance quantities to be calculated from the task, aircraft, and pilot - aircraft models, along with the methods to be used and the interpretation procedures to be applied. All objective evaluation items established through design and procurement requirements for flight testing, can be predicted by means of a properly selected model or manned flight simulation.

It often occurs during design and development that performance quantities are identified that relate to flying qualities in previously unrecognized ways. Such quantities are often related to control or weapons system behavior, and can best be studied using a combination of prediction methods based on analytic models and manned flight simulation. Subjective data obtained from manned flight simulation should be obtained in the same manner as in actual flight test. In interpreting this data, it should be kept in mind that activity of a simulation pilot is, in fact, only a representation of what a pilot would do in the actual aircraft.

Correlations of Pilot Ratings

The prediction of subjective evaluation is performed by postulating correlations of pilot ratings and comments with open and closed loop airplane and pilot model parameters, and performance evaluations.

Correlation of pilot ratings and comments with open loop airplane characteristics is the basis of many items in MIL-F-8785B. For sufficiently conventional aircraft dynamics, short period and dutch roll eigenvalues correlate with pilot ratings. For this reason, acceptable performance is judged when the corresponding eigenvalues are within the specified bounds of frequency and damping. Other open loop dynamics correlate with pilot comments and pilot ratings. Dutch roll amplitude and phasing, for example, are unpleasant to the pilot in cases identified by MIL-F-8785B. Unfortunately, such correlations obtain only for aircraft that have similar dynamic response modes.

Correlations of pilot ratings and comments with closed loop model and performance parameters are applicable to a larger class of aircraft than the open loop correlations. In this case, the correlations are in terms of how well the precision task model is carried out along with some knowledge of predicted pilot activity as reflected in pilot model parameters. There are three basically different methods currently under development or in use.

- Payoff Functionals. These are usually computed by means of optimal control theory and give a weighted blend of output statistics and pilot activity. The values of the optimized functional are correlated with pilot ratings.
- Pilot Rating Formulas. These models postulate that pilot workload is equivalent to pilot compensation so that pilot ratings become functions of pilot model parameters and output statistics weighted in a suitable manner.
- Multi-Parameter Performance Correlations. These methods recognize that many tasks consist of several mutually compromising objectives that the pilot must trade off against one another. By correlating ratings and comments with these tradeoff elements, regions of output statistics that correlate with ratings can be demonstrated without assuming functional definitions of pilot ratings or pilot workload.

Analysis and Prediction Methods

It is extremely important to understand the distinction between analysis methods and prediction methods. Inasmuch as both are used to generate data that is compared against specification criteria, it is natural that confusion exists about the roles of analysis and prediction.

As stated above, compliance with a procurement specification item must be on the basis of aircraft evaluation data obtained from flight test. This data may be transformable in certain ways, such as calculating short period eigenvalues from flight test aerodynamic data, that involve minimal assumptions on the model. Such highly reliable and validated analysis methods simply transform flight test data into a different form.

Prediction methods, on the other hand, are developed for use in design and development as a guide when flight test data are not available. It may well be the case that prediction methods have been instrumental in defining test items and corresponding criteria, but this in no way implies that data generated by these methods are suitable for demonstrating compliance and hence justifying procurement. This is especially true of pilot - aircraft methods, and pilot rating prediction in particular.

INTERPRETATION OF FLYING QUALITIES

The above discussion of the definition and objectives of flying qualities emphasized two principles:

- Formulating flying qualities questions in terms of a particular aircraft and its procurement and design objectives.
- Defining required flying qualities models of task, aircraft or pilot-aircraft, and evaluation, independent of computational algorithms.

These principles implicitly assume that for whatever problem formulation may be developed, suitable means for flying qualities evaluation, specification, and prediction are available. The goal now is to show how flying qualities defined by these methods can be interpreted in terms of specific numerical quantities and computational techniques.

Flying qualities is defined above in terms of its three areas of application: evaluation, specification, and prediction. Moreover, it was shown that the implementation of the basic principles of flying qualities leads to a choice of evaluation items independent of methodology from which specification items can be derived along with appropriate prediction techniques for aircraft design and development. For these reasons, the interpretations of evaluation, specification and prediction will be discussed in that order.

EVALUATION METHODS

Evaluation was defined to be the process of assigning three kinds of data to a specific airplane:

- objective - numerical measures through instrumentation
- subjective - pilot comments and ratings
- analytical - behavior of mathematical aircraft or pilot-aircraft models.

Once these evaluation data are obtained, they can be compared against specification criteria and a judgment of flying qualities goodness can then be made.

The principal source of both objective and subjective evaluation data is, of course, flight testing and eventually operational experience. Since evaluation data is mainly used to compare against procurement criteria, operational data is usually not available.

This means that the flight test programs must be sufficiently representative of the operational experience to give a realistic description of airplane capability.

Flight test procedures have been developed and refined in conjunction with aircraft development and operational aircraft experience, and effective test maneuvers and instrumentation have been developed. This experience has been exclusively concerned with defining how the airplane is to be tested, what tasks are to be flown, what measurements best reflect the resulting performance, and how the pilots are to be trained, introduced to the tasks, and questioned. The emphasis of flight test methodology on obtaining evaluation data (again contrasted to comparing the evaluation data against criteria and making judgments) in terms of the behavior of a specific airplane is in complete accordance with the basic principles of flying qualities as presented above. For this reason, the concerns of flying qualities should be dictated by current flight test practice and trends, and not by convenient computer codes.

The main problem in flight testing is the selection of flight test items. It is important to keep in mind that these items are chosen not as typical operational flight tasks, but as sources of evaluation data that will be as discriminating as possible when used for comparison against design and procurement criteria. This is made most clear in Reference 1 by Thomas Twisdale of the Air Force Flight Test Center:

> "It is very important not to confuse tracking test techniques with the operational tracking and gun firing techniques associated with an actual combat encounter. Tracking test techniques are a powerful tool for identifying and defining handling qualities deficiencies and optimizing flight control systems. These techniques were specifically developed to elicit engineering data which may be used to improve the handling characteristics of the airplane. In this respect it is certainly expected that the results of tracking test techniques (a better handling airplane) will favorably impact the operational pilot's ability to control his aircraft during combat encounters. But it would be a mistake to assume that the data gathered using these techniques directly reflect such overall mission effectiveness parameters as the likelihood of a kill. The overall combat effectiveness of the airplane is a function of many considerations. Tracking test techniques provide a measure of that portion of mission effectiveness which is related to the pilot's ability to precisely control the aircraft attitude."

The tracking test techniques to which Twisdale refers, concern tracking a target aircraft during smooth wind-up or constant angle-of-attack turns. Data of this kind has proved highly useful in a number of aircraft development programs, and this approach to flight testing is firmly established.

Unfortunately, these developments in aircraft evaluation methods have not been matched in flying qualities specification and prediction techniques. Presently there are no criteria in MIL-F-8785B for target tracking performance based on standardized target tracking tasks. This is in part a result of the previous lack of suitable established prediction methods necessary for such criteria to be useful during preliminary design and aircraft development.

Another tracking technique that is gaining prominence in flight testing is in recognition that a major concern of the pilot is his ability to carry out discrete aircraft flight path or attitude corrections quickly without resulting difficulties such as overshoot, residual oscillations, or unfavorable mode coupling. Discrete-error tracking tasks are now frequently used in flight test and flight simulation programs. One of the first and most important flying qualities flight test programs to incorporate these tasks was the study performed in 1970 by T. Peter Neal and Rogers E. Smith using the NT-33 variable stability in-flight simulator, Reference 7. It is useful to consider the pilot evaluation tasks that were used in this study.

An examination of these task items reveals that other than the IFR continuous random tracking task, all flight task items were of a discrete nature, either to make specific control corrections, or to perform open loop maneuvers. In Section 6.2 of Reference 7 titled "The Pilot's View of Good Tracking Performance," Neal and Smith comment:

> "The first step in the analysis is to identify the performance which the pilot is trying to achieve when he "adapts" to an airplane configuration. The pilot comments indicate quite clearly that he wants to acquire the target quickly and predictably, with a minimum of overshoot and oscillation. The question that remains is how to translate this observation into mathematical terms."

This "translation" properly belongs to the subjects of flying qualities specification and prediction and has been addressed in References 3 and 8.

It is interesting to contrast the flight test methods of tracking target aircraft in wind-up turns with the flight test evaluation items based on discrete control corrections and maneuvers. They are in no way mutually exclusive; rather they simply reflect evaluation emphasis on objective items (tracking statistics) or subjective items (pilot ratings and comments).

SPECIFICATION METHODS

The extensive integration of controls, weapons, navigation, and avionics systems in current aircraft designs implies that flying qualities specification items of aircraft performance for all mission tasks cannot be independent. For this reason, the following discussion of specification and prediction will apply to those kinds of items currently covered by MIL-F-8785B along with precision piloted tasks. In this sense, there are two objectives of design or procurement specification items:

- to guarantee required aircraft capabilities
- to guarantee pilot acceptance.

Ideally, if the basic postulate of flying qualities as stated in the Introduction has been followed, and an appropriate set of evaluation items has been established, these two specification goals are easy to achieve. All that is required for the first is to place inequality constraints on the evaluation measures, and for the second is to require favorable pilot ratings and comments for all test flight experience. There are two reasons why this does not currently suffice in practice:

- Appropriate sets of objective evaluation items have not been established and verified as sufficient for procurement.
- Specification items must be predictable during design and development; however, means of predicting performance and pilot acceptance for non-standard control and unconventional aircraft configurations are not fully developed.

For flying qualities as a subject to be fully responsive to the needs of current aircraft design and procurement agencies, these limitations on specification must be overcome. Two important achievements are required. First, in accordance with the above analysis of aircraft evaluation, it must be recognized that appropriate evaluation data sets should be established in terms of particular aircraft design and procurement objectives. As stated above, the guidance in doing this should be supplied by flight test and flight operational experience. Second, flying qualities as a subject must refrain from rephrasing all questions in terms of readily available or fashionable problem formulations, and instead respond by providing techniques for predicting specification compliance for all items deriving from the evaluation methods currently being used or being developed by flight test practice.

There are three kinds of evaluation data, objective, subjective, and analytical, that can be used to develop specification items to guarantee aircraft capability and to guarantee pilot acceptance. The ways in which these data are used, and the corresponding requirements of associated prediction methods will now be briefly summarized.

Specification and Prediction of Aircraft Capability

Open loop aircraft capabilities such as maximum attitude rates, rise times, mode phasing, trimmability and other such performance measures constitute much of the current MIL-F-8785B specification. Many of these items will remain appropriate for future aircraft procurement, and sufficient prediction methods exist based on transform, state variable, and time history representations of the aircraft and control system.

Since subjective evaluation is by definition a matter of pilot acceptance, the remaining approach to aircraft capability specification and prediction is by means of objective evaluation measures deriving from precision piloted tasks. For objective evaluation items developed for critical or representative flight tasks, specification items can be expressed in terms of statistics obtained by measurements in the time domain; that is, by observing what the aircraft is doing. Quantities such as mean and standard deviations of tracking errors, percent of time within allowable tolerances, and probabilities of exceedances are all easily measurable, but must also be predictable for any specification item based on them to be useful in aircraft design. Such prediction methods are now largely available, and given task and evaluation models as defined above, pilot-aircraft models can now be established and exercised to generate the required objective data predictions.

Specification and Prediction of Pilot Acceptance

The objective of MIL-F-8785B is to assure flying qualities that are "clearly adequate for the mission flight phase" when compliance is demonstrated. This is done by comparing one- or two-dimensional analytical or objective evaluation measures against inequalities (one-dimensional data) or boundaries (two-dimensional data) that have been validated to correlate with goodness of flying qualities defined in terms of Level 1 (clearly adequate), Level 2 (adequate but with increased pilot workload or degradation in performance), and Level 3 (safe flight, but inadequate flying qualities). It should be noted that the analytical and objective data correlated with Levels in MIL-F-8785B are performance measures of the open loop airplane only, consisting of such items as airframe or augmented airframe frequency versus damping, roll-sideslip phase and amplitude, and controller gradient forces. All required evaluation data for MIL-F-8785B comparison are easily predicted.

This MIL-F-8785B approach to flying qualities specification by correlating one- or two-dimensional evaluation open loop data with Levels of flying qualities has been highly successful, and it is natural to extend this method to correlate closed loop objective evaluation data as well. The use of closed loop pilot-aircraft prediction models allows a much closer correspondence between specification items and design and procurement objectives. Supporting predictive means exist for a wide variety of general and representative evaluation data items that may be correlated in a one- or two-dimensional way with Levels of flying qualities.

This task and evaluation generality manifests itself in two fundamental ways:

- Transient or steady-state precision piloted tasks.
- Single or multiple task pilot activity for a given flight phase.

A survey of the four corresponding basic closed loop pilot-aircraft prediction models is presented in Reference 9.

So far, the discussion of pilot acceptance has concerned the use and prediction of analytical and objective evaluation data. In addition to these correlations, the direct use of pilot ratings should be considered. Experience has shown that current methods of training test pilots and introducing them to prototype or development aircraft leads to accurate predictions of acceptance by pilots of the resulting operational aircraft. For this reason, the final judgment of pilot acceptance of a given airplane rests with pilot ratings obtained during flight test programs. Specification of pilot acceptance simply becomes a matter of requiring acceptable pilot ratings during all flight test evaluation studies. During design, before the aircraft is available to a test pilot, correlations of evaluation measures can be used to predict acceptance as discussed above. There is, however, another approach: pilot rating prediction.

Several methods for predicting pilot ratings have demonstrated the ability to "predict" ratings for previously existing sources of experimental data. These methods postulate that the performance and workload aspects of the Cooper Harper rating scale are weighted by the pilot according to a linear functional, or can be predicted using optimal control and a pilot model performance index. A survey of the demonstrations of pilot rating prediction reveals that a number of underlying assumptions will have to be justified before this attractive approach can gain acceptance as a prediction method, let alone as a basis of flying qualities specification.

First of all, pilot compensation models have been developed and validated by linear identification methods, and assume that the pilot operates as a time invariant continuous controller who generates control commands as a fixed blend of tracking error and its derivatives. The use of pilot models for rating prediction must assume that the pilot model parameters are related to workload, since aircraft tracking performance cannot be correlated with pilot model gains, leads, and lags. It must be further assumed that all workload aspects of flying qualities are manifested in the model coefficients.

Now consider pilot rating assumptions. It is assumed that aircraft performance can be normalized or calibrated in a manner that reflects a pilot's concern with adequate flying qualities. It is further assumed that the workload measure is a linear functional of the pilot model coefficients adjusted for optimal predicted pilot ratings, that the pilot rating is a linear functional of both performance and workload, and that the weighting coefficients are constants.

It should be noted that justification of these or similar assumptions is not required to extend pilot rating correlation (as contrasted to prediction) methods as practiced by MIL-F-8785B to include closed loop performance measures. Furthermore, it has been shown that by suitable choices of performance measures, tradeoff aspects of piloted experience can be identified, and correlations with pilot comments as well as pilot ratings can be obtained, Reference 8.

In summary, specification items must be developed in terms of the most meaningful evaluation items that flight test, flight simulation, and operational experience can evolve. Once these items are identified, at least the following conditions must be met for the item to be accepted as a procurement specification criterion:

- The specification item must be numerical.
- The specification item must correlate with pilot comments and pilot ratings.
- The specification item must be easily measured in flight test or flight simulation.
- The specification item must be reliably predictable by analytical means for use in early design and development.

- The method that predicts the specification item must be applicable in a completely standardized form that incorporates the most general models of the candidate aircraft required.
- The specification item must be valid for all current and acceptable aircraft, and must exclude poor or unacceptable aircraft.

FLYING QUALITIES PREDICTION METHODS

The preceding analysis of aircraft evaluation and specification has promoted the following two principles as a basis for developing the subject of flying qualities in a way responsive to the needs of advanced aircraft development:

- Evaluation and specification items should be developed for individual airplanes in a way that most generally reflects the operational requirements; flight test practice is a good guide for this.
- Specification items, to be useful in design, development, and aircraft improvement, must be supported by analytical prediction methods responsive to the full generality of the flight test evaluation items; it no longer suffices to limit flying qualities prediction to those quantities that can be calculated by steady-state, linearized, and transform methods.

Most pilot-aircraft prediction analysis has been concerned with a single axis tracking task and although this does not represent many flight phases well, it nevertheless is a useful description of a pilot's activity during precision maneuvers such as weapon delivery and landing. By extending flying qualities analysis from the consideration of open loop eigenvalues to the dynamically more complete model of the pilot's loop closure, approximations to the closed loop control can be obtained. From this standpoint, pilot — aircraft modeling work has been concerned with matching a simulator pilot's gain and phase as identified by linear means, and assessing the characteristics of the loop closure by methods of classical or optimal control theory.

The models developed by these means can also be used to predict the closed loop tracking statistics of a piloted task such as attitude stabilization in turbulence or following a randomly generated command. For such problems, the models show two important characteristics:

- Fixed form gain — lead — delay models agree within a few percent with flight simulation tracking error statistics.
- Motivated skilled pilots asymptotically trained achieve nearly identical tracking error statistics.

In this way, pilot — aircraft models are accurate predictors of what operational piloted aircraft can do during precise tracking. However, there are limitations on this approach, both in terms of the applicability of the model, and in terms of how the results have been interpreted. For example:

- Random tracking commands are difficult to relate to operational experience.
- Much pilot activity and concern is with the ability to make precision discrete changes in aircraft attitude, flight path or flight condition. These cannot be represented in a time-invariant manner.
- Flight simulation and pilot — vehicle analysis of a continuous tracking task are not representative of the full scope of aircraft flying qualities and in no sense "do the whole job."
- The common practice of obtaining pilot ratings during highly restricted precision tracking flight simulations has led to the incorrect assumption that these ratings reflect an overall rating of the aircraft dynamics simulated. Ratings obtained in this way reflect only compensation aspects of workload, and pilot estimates of performance are based only on experience during the flight simulation, which is not comparable to actual flight experience. For these reasons, pilot rating prediction methods that are adjusted to such simulation data cannot be regarded as validated predictors of overall ratings obtained from flight test.
- The reliance on single task continuous prediction methods assumes that flying qualities of an airplane can be fully studied by looking at each piloted task component separately. It is now widely recognized that the pilot has available limited attention, sensory, and motor information channel capacities which produce task interference effects that are severe limitations on performance in multi-task flight such as landing and weapon delivery.
- A practical limitation on the use and acceptance of single task time-invariant pilot — aircraft prediction methods has been the failure of most studies on the subject to subordinate the specific model components to the overall concerns of what the aircraft does, and how well a pilot can make it perform.
- Reports on pilot-aircraft methods often present elaborate arguments concerning model parameters rather than derive time domain statistics and properties that can be related to flight simulation and flight test. As long as this tendency persists, the aircraft control design community will continue to regard pilot — aircraft methods as simply "pilot modeling," an esoteric subject not fully responsive to design and development requirements.

It was indicated above that a pilot's control of an airplane can be conveniently classified in generic terms of whether his particular flight task is continuous steady-state or transient and intermittent, and whether he is faced with only one attention demand, or if several independent activities are under his control. The authors have recently completed a study for the USAF Flight Dynamics Laboratory that demonstrates how these categories of flying qualities problems can be studied in accordance with the above principles. Reference 3 presents a comprehensive account of these methods, and Reference 9 gives a brief summary of these results along with examples of how flying qualities prediction methods can be developed.

REFERENCES

1. Twisdale, Thomas R., and Franklin, David L., Tracking Test Techniques for Handling Qualities Evaluation, AFFTC-TD-75-1, Air Force Flight Test Center, Edwards Air Force Base, California, May 1975.

2. Moorhouse, D.J., The History and Future of U.S. Military Flying Qualities Specifications, American Institute of Aeronautics and Astronautics Paper 79-0402, Seventeenth Aerospace Sciences Meeting, New Orleans, Louisiana, January 1979.

3. Onstott, E.D., and Faulkner, W.H., Prediction, Evaluation, and Specification of Closed Loop and Multiaxis Flying Qualities, AFFDL-TR-78-3, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, February 1978.

4. Harper, R.P., and Cooper, G.E., A Revised Pilot Rating Scale for the Evaluation of Handling Qualities, Cornell Aeronautical Laboratory Report No. 153, September 1966.

5. Anonymous, Military Specification, Flying Qualities of Piloted Airplanes, MIL-F-8785B, August 1969.

6. Chalk, C.R., et al, Background Information and User Guide for MIL-F-8785B (ASG), "Military Specification — Flying Qualities of Piloted Airplanes," AFFDL-TR-69-72, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, August 1969.

7. Neal, T.P., and Smith, R.E., An In-Flight Investigation to Develop Control System Design Criteria for Fighter Airplanes, Volumes I and II, AFFDL-TR-70-74, Air Force Flight Dynamics Laboratory, Wright- Patterson Air Force Base, Ohio, December 1970.

8. Onstott, E.D., and Faulkner, W.H., "Discrete Maneuver Pilot Models for Flying Qualities Evaluation," Journal of Guidance and Control, Vol. 1, No. 2, March-April 1978.

9. Onstott, E.D., and Faulkner, W.H., Definition and Interpretation of Flying Qualities, NOR-79-22, Northrop Corporation, Hawthorne, California, March 1979.

WORKING SESSION

Design Criteria

A good cross section of government and industry representatives gathered to hear two fine presentations. The first was brought by Duane Choo of Northrop who described difficulties they encountered in designing the A-9 to meet the lower Level 1 boundary of the short period frequency requirement. A written version of Mr Choo's presentation follows this summary.

The second presentation was given by Jim Buckley of McDonnell Aircraft describing their experience in developing a Six-Degree-of-Freedom-Transfer-Function Fixed-Based Flight Simulation. The objectives were to investigate integrator "droop" effects on aircraft handling qualities and to validate this new concept in simulation. Mr Buckley described the physical characteristics of the simulator and target tracking task. A typical transfer function, n_z/F_s consisted of a first-order numerator, gain, and third-order denominator to represent the "equivalent" effects of a proportional plus integral flight control system. Other degrees of freedom were also modified by appropriate transfer functions. Results showed pilot ratings versus equivalent Control Anticipation Parameter, $\omega^2 n_{sp}/(n/\alpha)$, that appear reasonable. Stick force gradients were also varied to obtain pilot opinion as a function of equivalent short period frequency. To implement the equivalent model on the simulator, the transfer function representations were solved (integrated) neglecting gravity. Then the first-order effects of the nonlinear gravity and coupling terms were added, giving the full body axis rates. These were (Euler) transformed to output the aircraft motion. A few corrections were required, but overall the pilots found that it "flew like an airplane." The entire simulation used less than 100K octal core size and one-tenth of the 50 msec available frame time. Overall it performed very well at one-third the cost of a conventional simulation.

The final topic of discussion was raised by Lt Rob Crombie of the Flight Dynamics Laboratory. Lt Crombie desired comments on a proposed inhouse effort to generate design criteria for statically unstable aircraft. This has been documented following this Summary. Almost all comments agreed that something like this is needed. Areas mentioned to examine in this regard were the ability to trim in a turbulent environment, deep stall recovery, roll-induced interial coupling (pitch-up), and control system stability when employing high gains.

The final paper in this section was submitted by Dr Jack McAllister of General Dynamics. It points out some important lessons in the design of direct lift control modes.

ROBERT B. CROMBIE, 1/Lt, USAF
Recorder

TIMOTHY P. SWEENEY, ASD/ENFTC
Moderator

COMMENTS ON
MIL-F-8785B (ASG) LOWER LIMIT REQUIREMENTS
ON LONGITUDINAL SHORT-PERIOD FREQUENCY RESPONSE
(BASED ON NORTHROP A-9)

DUANE CHOO
AERODYNAMIC DESIGN
NORTHROP CORPORATION

Introduction

The comments presented here are based on Northrop A-9 prototype close air support aircraft. During the prototype fly-off program the un-augmented A-9 exhibited a pitch sensitivity problem in the form of load factor overshoots while recovering from 60-degree dive bombings. These phenomena occurred even though the A-9 satisfied level 1 requirements as specified in MIL-8785B (ASG).

A-9 Design Criteria

The basic design approach was to provide a low control anticipation parameter (CAP), (W^2/n_α) and low maneuvering force gradient for good weapons delivery accuracy. The damping ratio was to be at least .5 as required by the AX specification. The desirability of this approach was indicated by Northrop simulation studies. During the studies the emphasis was on weapons delivery accuracy using the direct sideforce control system, although some other maneuvers such as pull-outs were performed. There was no indication of adverse flying qualities due to low Wnsp and Fs/n.

Figures 1 and 2 demonstrate the agreement between the predicted and the flight test obtained data as well as compliance with Level 1 requirements. The flight test Wnsp and ζsp were obtained using the frequency response method where pilots performed sinusoidal maneuvers at various input frequencies. The flight test acceleration sensitivity parameter n_α was obtained by windup-turn maneuvers.

Flight Test Maneuvers and Problems

One of the maneuvers that had to be performed during the competition flights was weapons delivery maneuvers, where the pilot initiated a roll-in at nominal 10,000 ft altitude and dived at 60 degrees to release a bomb at 350 kt and 5,000 ft altitude. After the release he was to perform a 4-g pull-out, not to exceed the allowable limit load factor dictated by the flight safety requirements (4.3gs to 4.8gs). During these maneuvers the A-9 exhibited some unexpected flying qualities problems: pitch oscillation of $\pm$0.5g during tracking and load factor exceedance of up to 2g's during pull-outs. Except for the weapon delivery phase the flight characteristics were generally satisfactory. Following these the weapons delivery phase of the flight test was terminated until a "fix" was found to alleviate the problem. The short term "fix" was to increase the stick force gradient (F_s/n) to reduce the pitch sensitivity. The aircraft was then acceptable to continue flight test. It should be emphasized here that the overshoots occurred only during steep dives, and no other maneuvers including 25° and 45° dive bombings experienced these.

Figure 3 is a typical A-9 weapons delivery time history of the 60° dive profile. The pitch oscillation during tracking and load factor-overshoot during pull-out are readily discernible. In these maneuvers the pilots attempted to delay the pull-out and then attain the desired 4g in short time to reduce the slant range at release for accurate bombing. The roll-in altitude and airspeed were selected to give a maximum of 6 seconds tracking time.

Pilot's View of Problem

The pilots felt that during the pull-out there was an extended period of time before the aircraft began to respond (Page 20, Ref. 4). The relatively large lag (.7 seconds in the example in Figure 3) between the load factor rise and the pilot's input is probably responsible for this impression of sluggish response. To overcome this initial sluggishness the pilot would probably apply a larger than normal input resulting in overdriving the aircraft. This characteristics, in the presence of light stick force, may have cuased the overshoots. The high values of pilot gain generally associated with high stress or precision maneuver tends to decrease the closed-loop damping ratio and thus induce a mild pitch oscillation. At low short-period frequency, a relatively low pilot gain would result in neutral stability (Ref. 2). Some pilots apparently alleviated the overshoot problems by flying it smoothly, while others could not. These phenomena appear to be symptomatic of low short-period frequency aircraft.

It should be noted that some contributive causes, such as the pitch upset caused by the sideforce control, undoubtedly aggravated the situation, but it is believed that these played a relatively minor role.

Review of MIL-F-8785B (ASG) Lower Bounds Requirements

Figure 4 shows the results from two well known CAL in-flight simulation studies where four pilots participated in various simulation tasks to determine the effects of short-period frequency on flying qualities. For simplicity and clarity the faired curves rather than the actual test data points are used to construct Figure 5. In both tests the pilots chose the optimum stick force gradient, F_s/n, as much as possible. To this extent the effect of F_s/n on pilot rating was relatively minor.

Figure 5 shows pilot ratings as a function of CAP in linear scale. It is evident that there is a very steep gradient near the lower end of CAP value and the gradient is fairly flat for medium to high CAP value. These characteristics are evident on a plot in linear scale as opposed to the log scale in the spec. It appears that there is "flying qualities cliff" near the low value of CAP.

Figure 6 is intended to show the sensitivity of CAP. Near the lower value of CAP a 4%$\bar{c}$ change in maneuver margin is equivalent to approximately 2 points in PR and a 20% change in weight to pitch inertia ratio corresponds to 1 point in PR. The same changes in CAP would affect PR very little at higher CAP values.

Conclusions

Near the lower limit of Level 1 short-period frequency requirements, the following conclusions can be drawn:

a. There exists "flying qualities cliff".

b. CAP is very sensitive to maneuver margin and external store loadings.

c. There is large PR variation among pilots.

To accomodate high gain maneuvers it is suggested that a caution note may be in order to avoid "flying qualities cliff" near the low boundary of Level 1 requirements of short-period frequency response and stick force gradient.

<u>References</u>

1. DiFranco, D. A. "Flight Investigation of Longitudinal Short Period Frequency Requirements and PIO Tendencies", AFFDL-TR-66-168, June 1967.

2. Hall, G. W. "In-Flight Investigation of Longitudinal Short-Period Handling Characteristics of Wheel-Controlled Airplane", AFFDL-TR-68-91, August 1968.

3. Hoehne, V. O., Lockenour, J. L., etal, "An Examination of A-9A Aircraft Load Factor Exceedance", AFFDL/FGC/TM-72-23, December 1972.

4. Van Norman, C., etal, "A-9A Prototype Performance and Flying Qualities Evaluation", FTC-TR-73-10, March 1973.

FIG. 1

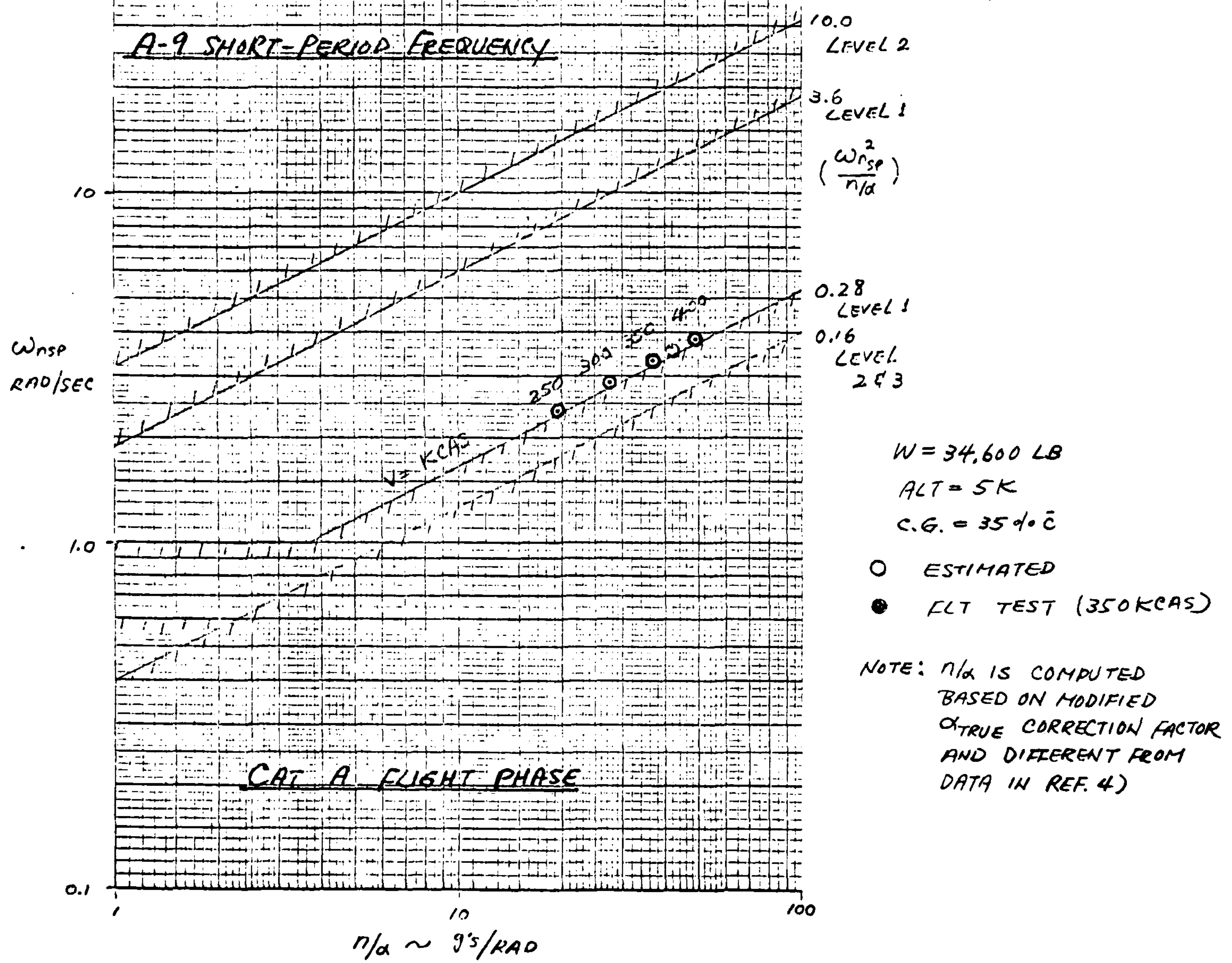
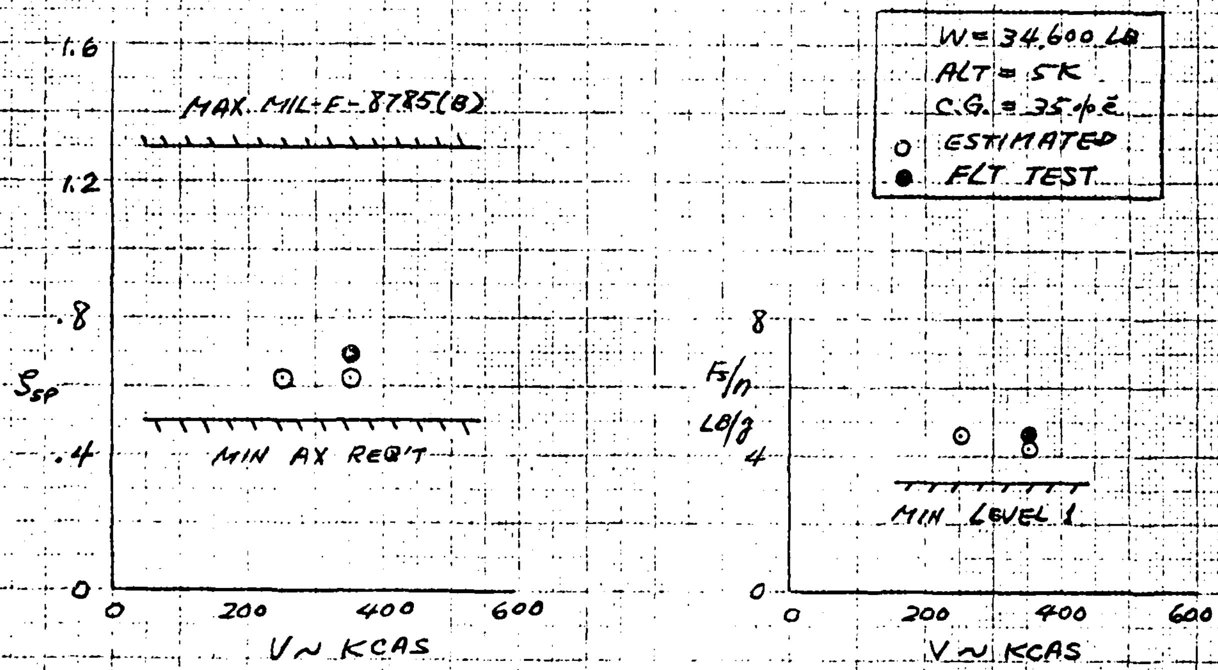

A-9 SHORT-PERIOD FREQUENCY
CAT A FLIGHT PHASE
$\omega_{n_{SP}}$ RAD/SEC
n/α ~ g's/RAD
10.0 LEVEL 2
3.6 LEVEL 1
$\left(\frac{\omega_{n_{SP}}^2}{n/\alpha}\right)$
0.28 LEVEL 1
0.16 LEVEL 2 & 3
V = KCAS
250
300
350
400
W = 34,600 LB
ALT = 5K
C.G. = 35% $\bar{c}$
ESTIMATED
FLT TEST (350 KCAS)
NOTE: n/α IS COMPUTED BASED ON MODIFIED α_{TRUE} CORRECTION FACTOR AND DIFFERENT FROM DATA IN REF. 4)

FIG 2

A-9 DAMPING RATO AND F_s/n_z



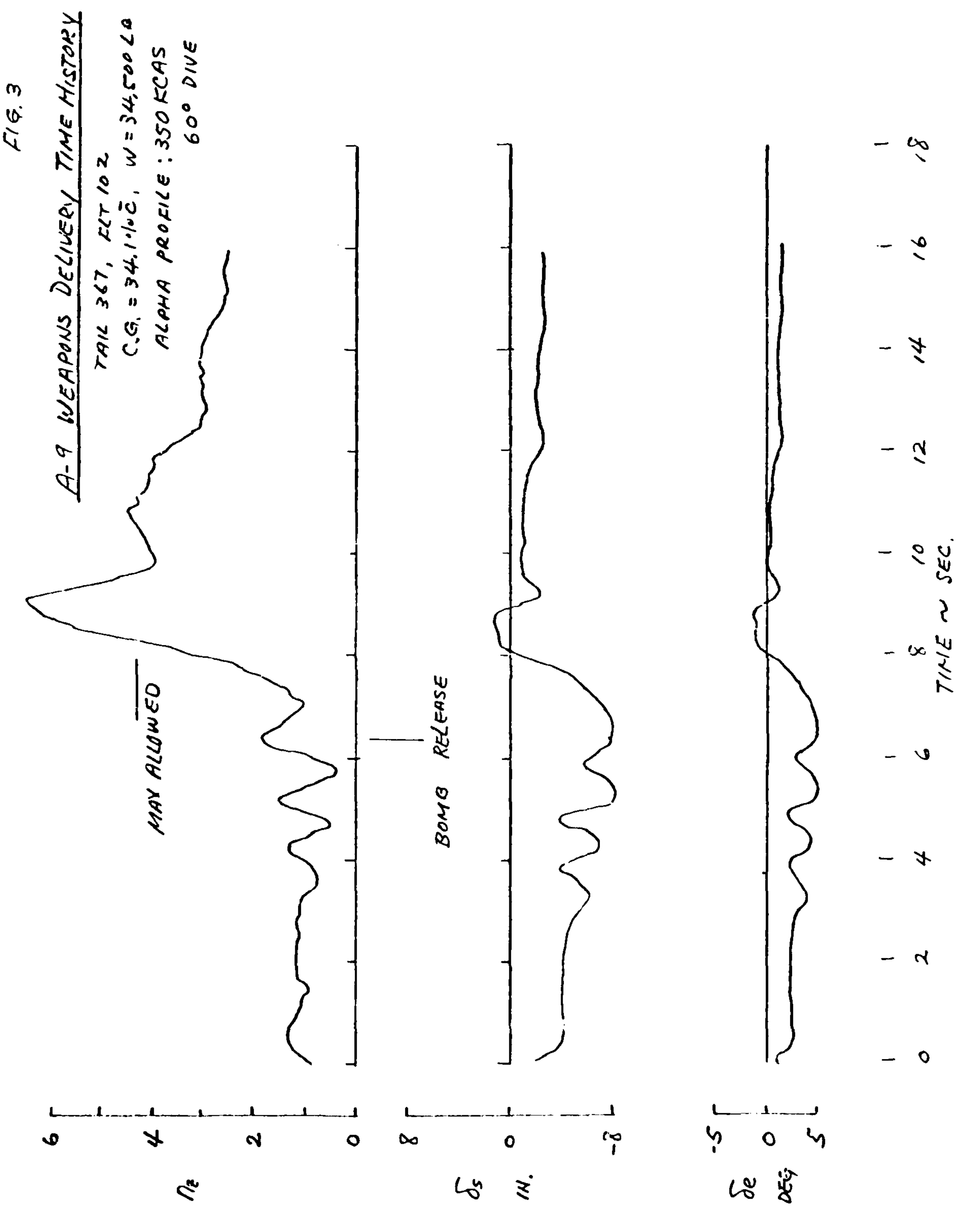
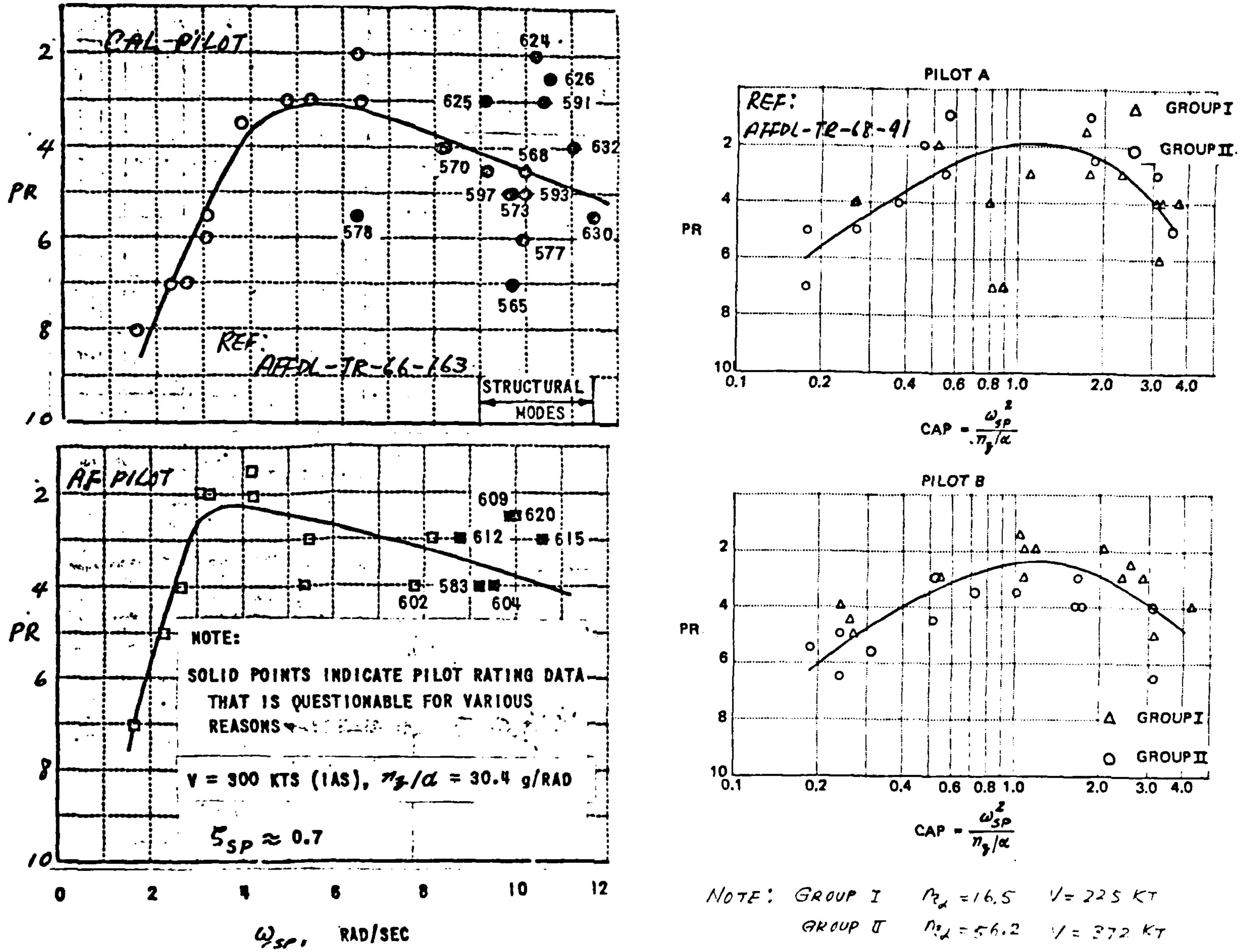


FIG. 3
A-9 WEAPONS DELIVERY TIME HISTORY
TAIL 367, FLT 102
C.G. = 34.1%C, W = 34,500 LB
ALPHA PROFILE: 350 KCAS
60° DIVE
MAX ALLOWED
BOMB RELEASE
n_z
δ_s IN.
δ_e DEG
0
2
4
6
8
-8
-5
5
0
2
4
6
8
10
12
14
16
18
TIME ~ SEC.

FIG. 4



CAL-PILOT
REF: AFFDL-TR-66-163
STRUCTURAL MODES
624
626
625
591
632
568
570
597
593
573
578
577
630
565
AF PILOT
609
620
612
615
583
602
604
NOTE:
SOLID POINTS INDICATE PILOT RATING DATA THAT IS QUESTIONABLE FOR VARIOUS REASONS
V = 300 KTS (IAS), n_z/α = 30.4 g/RAD
$\zeta_{SP} \approx 0.7$
PR
ω_{SP}, RAD/SEC
PILOT A
REF: AFFDL-TR-68-91
GROUP I
GROUP II
PR
CAP = $\frac{\omega_{SP}^2}{n_z/\alpha}$
PILOT B
GROUP I
GROUP II
PR
CAP = $\frac{\omega_{SP}^2}{n_z/\alpha}$
NOTE: GROUP I n_α = 16.5 V = 225 KT
GROUP II n_α = 56.2 V = 372 KT

FIG. 5

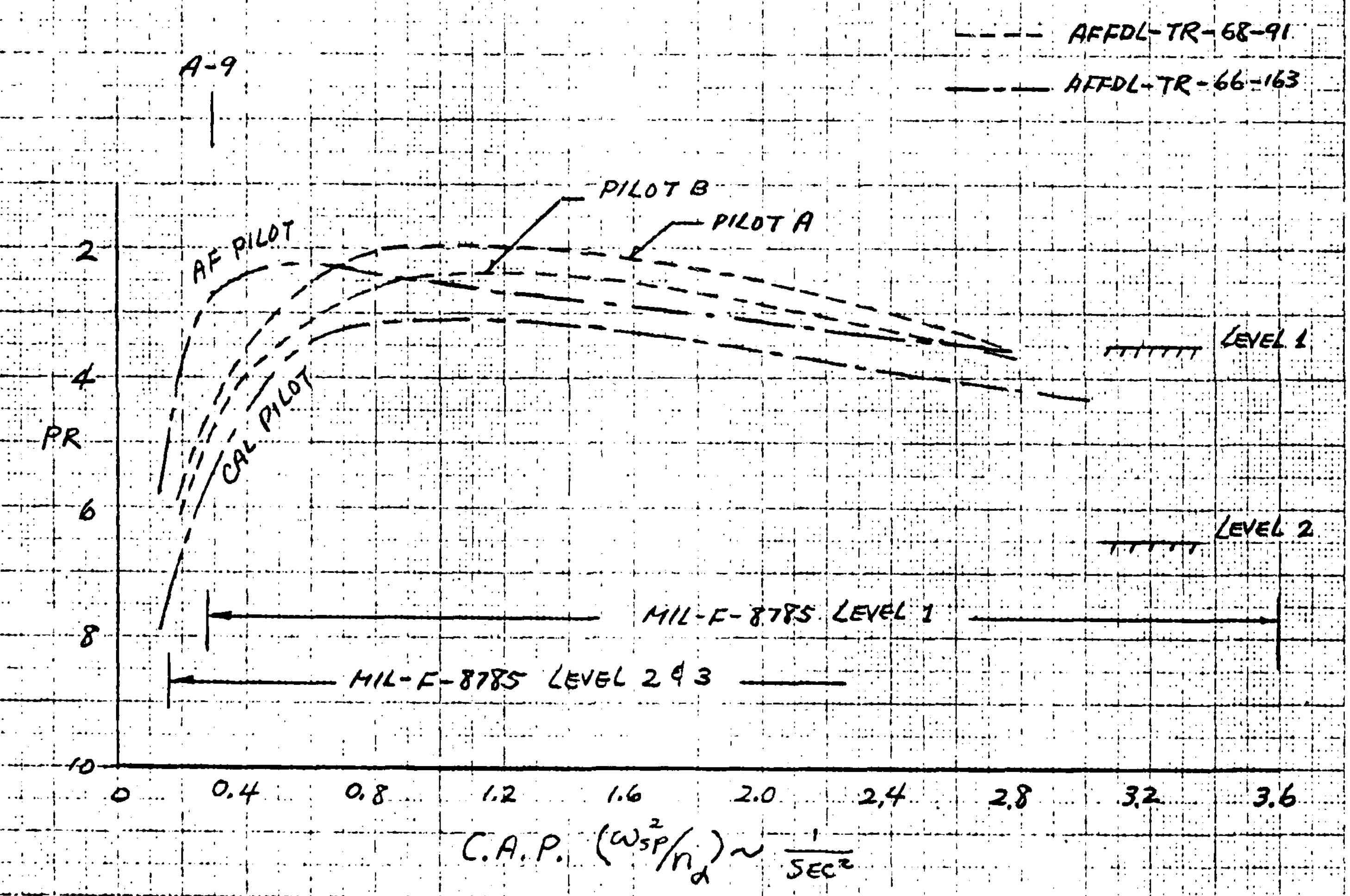
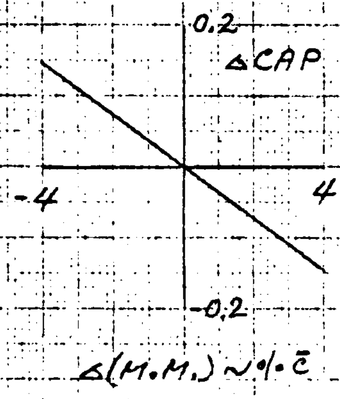
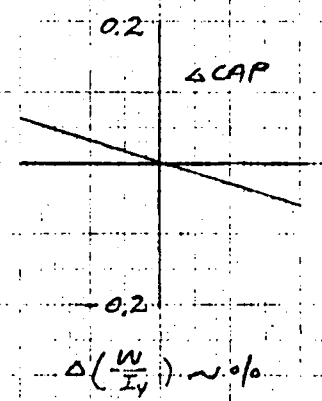

AFFDL-TR-68-91
AFFDL-TR-66-163
A-9
PILOT B
PILOT A
AF PILOT
CAL PILOT
LEVEL 1
LEVEL 2
PR
2
4
6
8
10
MIL-F-8785 LEVEL 1
MIL-F-8785 LEVEL 2 & 3
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
C.A.P. $(\omega_{SP}^2/n_\alpha) \sim \frac{1}{SEC^2}$

Fig. 6

A-9 C.A.P. Sensitivity





Note; Initial C.A.P. = 0.29

350 KCAS

C.G. = 35 % c̄

DEVELOPING DESIGN GUIDES FOR AIRCRAFT HAVING RELAXED STATIC STABILITY

by

Robert B. Crombie, 1Lt, USAF
Control Dynamics Branch
Flight Control Division
AFWAL/Flight Dynamics Laboratory

This brief paper outlines in-house work being done to develop design guides to help the preliminary designer account for the effects of pitch control deflection limits and actuation rate limits on advanced aircraft designs calling for large levels of negative static margin. Included in this paper are paragraphs describing the need for these design guides, the approach currently being taken, the expected results, and the current status. Any comments or suggestions on these topics will be appreciated.

Need. As advanced flight control systems are able to bear more and more of the burden of providing good aircraft flying qualities, the need for designing these aircraft to be aerodynamically stable has been relaxed. Minimum trim drag during supersonic flight frequently requires advanced aircraft to be statically unstable in the subsonic flight regime to levels previously thought to be too risky. Reduced static stability also offers enhanced agility to combat aircraft. Increased operational flexibility in terms of fuel, stores, and payload can be realized by expanding the allowable center of gravity envelope. All of these benefits can be realized by properly augmenting the aircraft flight control system within the limits of the available control power. Dangerous conditions can be encountered when the control power required exceeds that available. Good preliminary design practice requires that, as the required level of static instability is being estimated, an assessment be made of the control power required. Tradeoffs can then be made in terms of control surface size, location, deflection limits and actuator power.

The goal of this effort is to develop general preliminary design charts that will indicate, as a function of bare airframe static stability level, an estimate of the control power requirements to retain good aircraft flying qualities at low speeds in a turbulent atmosphere.

Methods. To accomplish this goal, two methods will be used. Both approaches utilize standard two degree of freedom aircraft equations of motion assuming constant forward speed. A simple flight control system will feed back pitch rate and angle of attack signals to provide short-period frequency and damping to levels specified in MIL-F-8785B. The flight conditions of crucial interest in this study are low-speed flight in turbulence where the flight control system will make large demands on the pitch control surface.

The first method is a computer program that generates linear and non-linear aircraft time responses to discrete (1-cosine) gust inputs. Each gust will be tuned to the damped natural frequency of the aircraft and flight control system as specified by MIL-F-8785B. Variations in the key total stability derivatives (e.g. M_w, Z_w) will be made. The non-linear effects of pitch control surface rate and deflection limits can easily be programmed.

The second method uses the describing function approach to non-linear systems analysis. Describing functions can model the effects of both rate limits and position saturation in terms of an equivalent linear system. Random turbulence or sinusoidal pilot inputs can be modelled using various forms of the describing function.

Expected Results. One result that follows naturally from the describing function approach is a measure of the degradation of flying qualities parameters ($\omega_{n_{sp}}$, ζ_{sp}) as limiting is encountered. Therefore, achievable levels of flying qualities can be plotted versus relaxed stability level.

A result of the non-linear gust response approach is a plot showing the location of a divergence boundary where a gust of given magnitude causes the pitch control surface to reach a deflection limit and diverge in angle of attack. Oscillatory divergences can be encountered when actuation rate limits are a factor.

Finally, linear time responses will show maximum response magnitudes as a function of relaxed stability level or the roots of the open-loop characteristic equation.

These results should be useful to the aircraft design community. In the preliminary design phase where significant parameters have been estimated (e.g. C_{L_α}, C_{m_α}, I_y, $C_{m_{\delta e}}$) one could use the above results to:

a. Evaluate whether pitch control limiting could take place at a given flight condition, and if so,

b. Evaluate quantitatively the degradation in flying qualities that would occur, or

c. Determine whether divergence will compromise a configuration's safety of flight, and

d. Design a pitch control surface that will be effective enough to avoid the above mentioned problem areas.

Status. As of mid-January 1980, the equations of motion and applicable transfer functions have been derived and programmed. Feedback gains have been derived analytically based upon the bare airframe characteristics and the desired levels of flying qualities parameters. The linear and non-linear time history programs have been checked out and gust responses are being tabulated. The applicable describing functions have been developed for random and sinusoidal inputs.

Summary. This paper has outlined an in-house effort to develop design guides for aircraft having relaxed static stability. The critical flight conditions to be investigated are turbulence and gust encounters at low speeds. The problem that arises is that the flight control system, which attempts to maintain good flying qualities, demands pitch control surface deflections or deflection rates that are inappropriate or unavailable. The effects of discrete gusts will be investigated using linear and non-linear time response computer programs. Random turbulence effects will be modelled using the describing function method of non-linear systems analysis. Expected results of each method have been described and the current status of the effort has been given.

SOME FLYING QUALITIES IMPLICATIONS OF AN AUTOMATED DIRECT LIFT MECHANIZATION

Dr. J. D. McAllister
General Dynamics, Fort Worth Division

One of the unique flight control modes developed and evaluated in the Fighter CCV Program, Reference 1, was an automated Direct Lift Mechanization named Maneuver Enhancement. A brief overview of this mechanization and the associated operating characteristics are given in Chart 1. The basic objective of the mode is to quicken A_N response by automatically commanding symmetrical flap deflection to minimize the transient difference between the pilot's A_N command and the measured aircraft response.

The most definitive pilot evaluation of the Maneuver Enhancement, in comparison to the baseline Prototype F-16 flight control system, was obtained in air-to-air tracking evaluations using the HQDT technique of Reference 2. The overwhelming consensus of the six evaluating pilots was that Maneuver Enhancement was a desirable improvement for air-to-air tracking. Chart 2 contains a sample comparison of tracking accuracy data obtained during one flight by a single pilot. The measured data confirms the pilot comment that tracking is improved with the Maneuver Enhancement mechanization. This particular pilot was also able to demonstrate further improvements in tracking accuracy by use of the manually commanded Direct Force Modes in conjunction with conventional manual control. However, other pilots were not able to improve tracking performance by combined manual commands to the Direct Force (A_N and A_Y) Modes and conventional control modes. This fact is illustrated in the statistical data summarized in Chart 3. Since the Maneuver Enhancement Mechanization involved only control law changes (no alteration of the cockpit controllers or basic pilot control technique), it is logical to conclude that the significant improvements due to Maneuver Enhancement will be evident in the dynamic response characteristics for this mode. These characteristics are considered below.

Charts 4 and 5 contain computed time history data for the Prototype F-16 and the Maneuver Enhancement Control Modes subject to a 1.0 g step change in the commanded A_N value. These data are for the nominal conditions of the in-flight HQDT evaluations discussed above, 0.8 Mach at 20,000 ft. altitude. Chart 4 demonstrates that Maneuver Enhancement quickens the A_N response while leaving the pitch rate and attitude responses essentially unaltered. Based upon these data, the equivalent lower order system representations of Maneuver Enhancement effects would be quite different depending upon the transfer function approximated, θ/F_S or A_N/F_S.

Quickening of the flight path response, $\Delta\gamma$, by Maneuver Enhancement is illustrated by Chart 5. Note that the quickened flight path response more nearly approximates the unaltered pitch attitude response, $\Delta\theta$. It is thus presumed that precise regulation of flight path as well as attitude are of basic importance for the manual air-to-air tracking task. In fact, it may be desirable to have essentially identical pitch angle and flight path responses such that all flight path changes are visually displayed to the pilot in terms of attitude changes.

In view of the above discussion, it is concluded that application of an equivalent systems approach to flight controls systems with automated Direct Lift should:

(1) Include consideration of all transfer functions relevant to the pilot task being considered.

(2) Involve specific checks to assure the resulting low order transfer functions preserve the key interrelationships between the pertinent transfer function characteristics.

REFERENCES

1. McAllister, J. D., et al, Fighter CCV Phase IV Report, AFFDL-TR-78-9, February 1978.

2. Twisdale, T. R. and Franklin, Capt. D. L., Tracking Test Techniques for Handling Qualities Evaluation, AFFTC-TD-75-1, May 1975.

AUTOMATIC MANEUVER ENHANCEMENT

(Integrated Direct Force Functions)

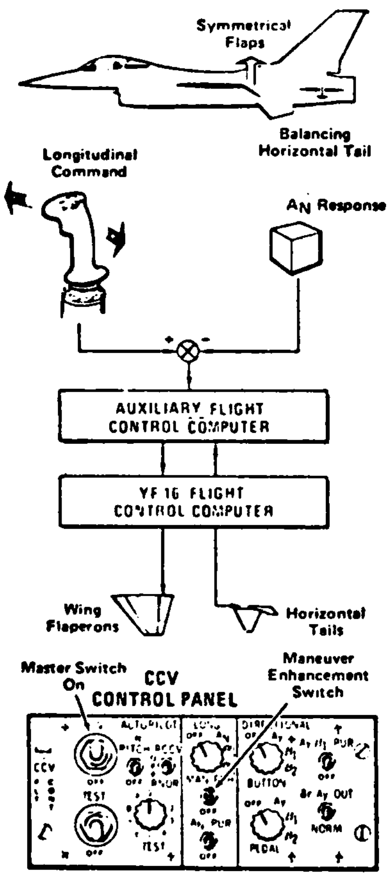
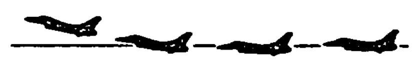
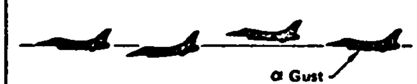
HARDWARE IMPLEMENTATION	CONTROL LAW MECHANIZATION	MODE CHARACTERISTICS	BENEFITS
	• Automatic Mechanization of Direct Lift • Flap Deflection Commanded by A_N Error (Difference Between Pilot A_N Command and Actual Aircraft A_N). • Flap Pitching Moments Cancelled by Maneuver Enhancement Mode • Flaperon/Horizontal Tail Interconnect	CCV MANEUVER QUICKENING  CONVENTIONAL PULL-UP 	• Quickened A_N Response During Initial Transients of Pilot Commanded Maneuvers • Noticeably Easier to Perform Precision Tasks Such as Constant g Turn at Constant Altitude
	MANEUVER ENHANCEMENT OFF	CCV GUST ALLEVIATION  CONVENTIONAL GUST RESPONSE 	• Reduces RMS Response to Random Turbulence • Reduces Peak A_N Response to Discrete Gust During Gust Strike and During Subsequent Response

CHART 1

FW76-204-VG7353
3 June 1976

WIND-UP TURN TRACKING COMPARISON
0.8M 22,000 FT.

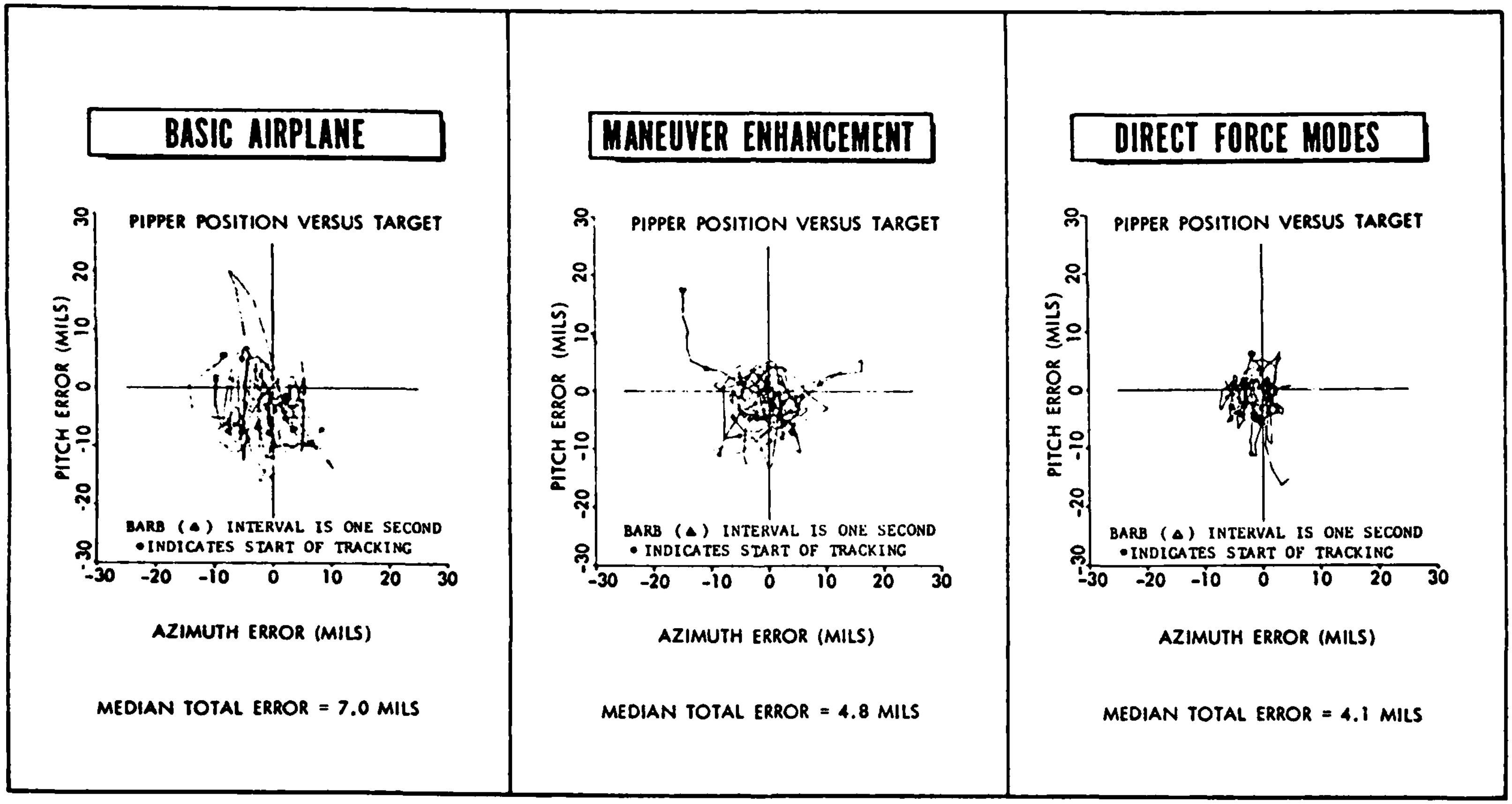


CHART 2

BOTH MECHANIZATION AND TRAINING ARE IMPORTANT

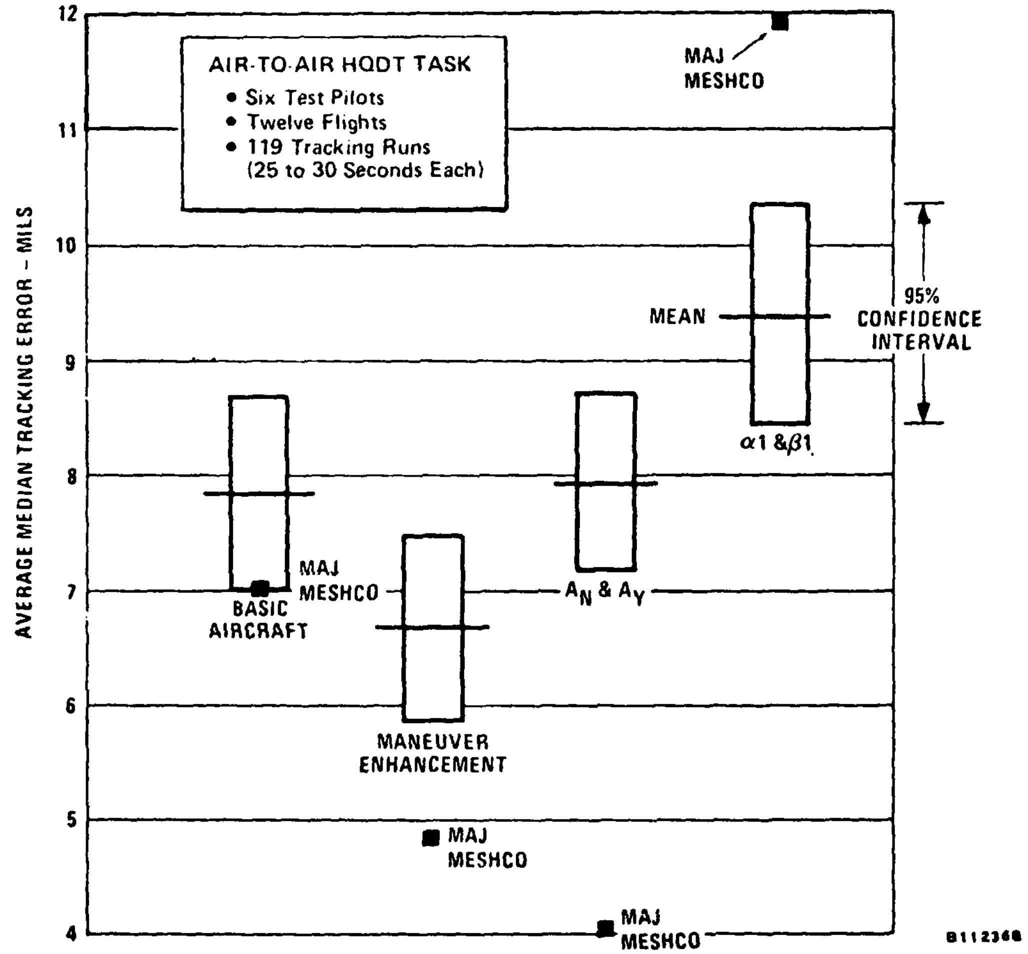


CHART 3

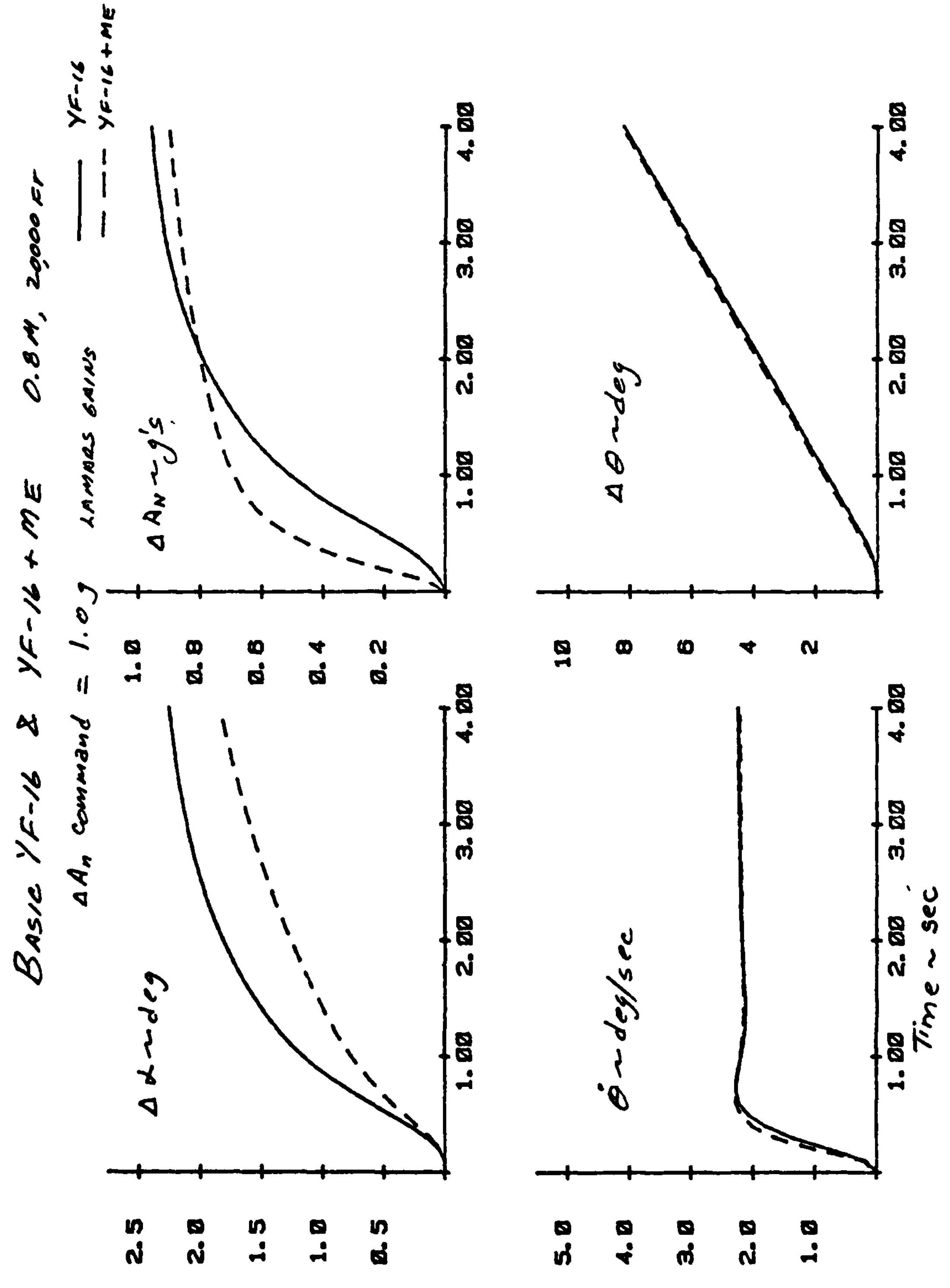
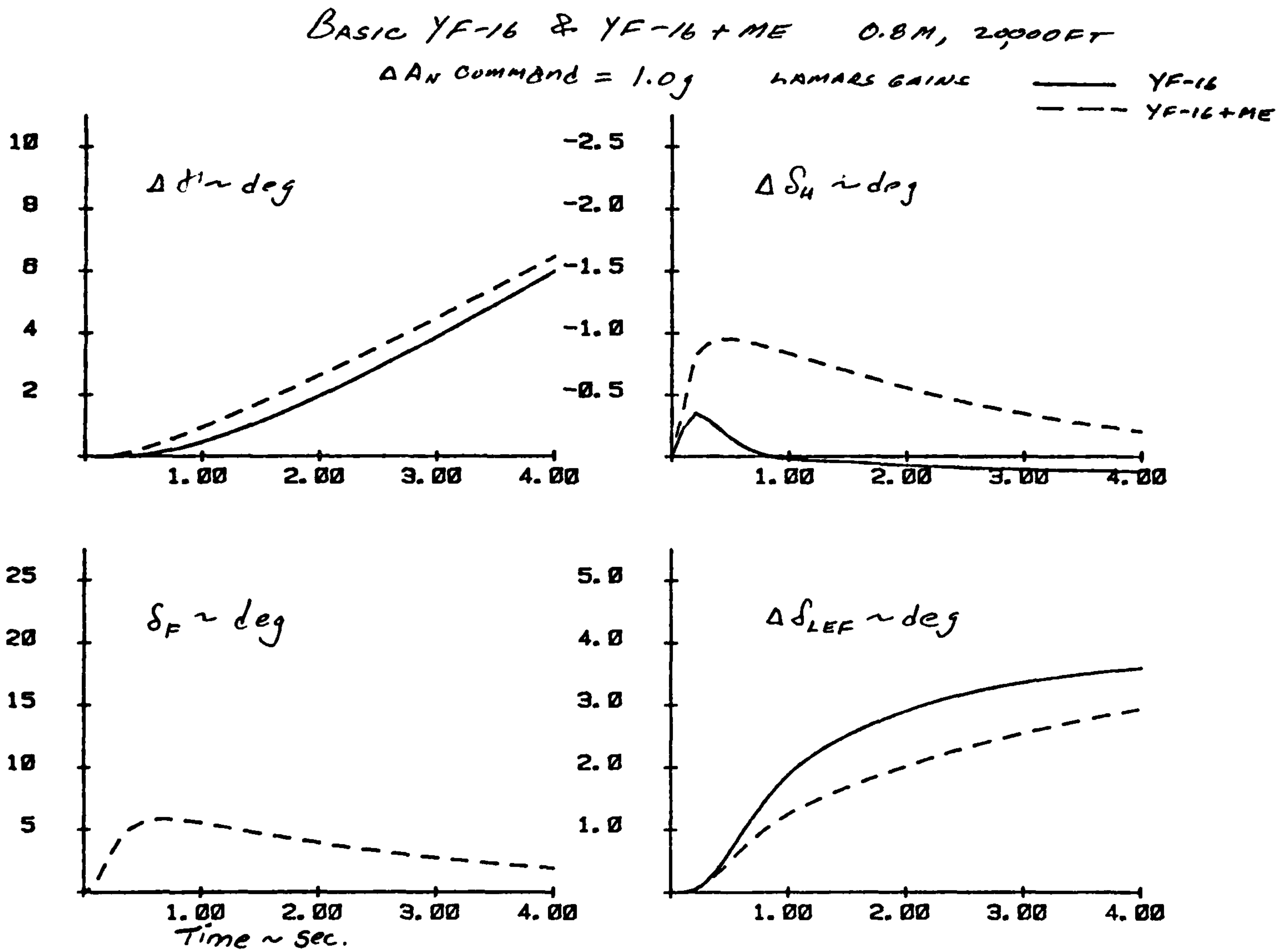

BASIC YF-16 & YF-16 + ME 0.8M, 20000 FT
ΔAn COMMAND = 1.0 g LAMBDAS GAINS
YF-16
YF-16 + ME
Δα ~ deg
ΔAN ~ g's
θ̇ ~ deg/sec
Δθ ~ deg
Time ~ sec
2.5
2.0
1.5
1.0
0.5
1.0
0.8
0.6
0.4
0.2
5.0
4.0
3.0
2.0
1.0
10
8
6
4
2
1.00
2.00
3.00
4.00

CHART 4



BASIC YF-16 & YF-16 + ME 0.8M, 20,000FT
ΔAN COMMAND = 1.0g
LAMARS GAINS
YF-16
YF-16 + ME
Δγ ~ deg
ΔδH ~ deg
δF ~ deg
ΔδLEF ~ deg
10
8
6
4
2
-2.5
-2.0
-1.5
-1.0
-0.5
25
20
15
10
5
5.0
4.0
3.0
2.0
1.0
1.00
2.00
3.00
4.00
Time ~ Sec.

CHART 5

WORKING SESSION

Specification Criteria

Moderator: David J. Moorhouse
AF Flight Dynamics Lab

The first order of business was Chick Chalk's review of the movie "10". Because of the fixed-base, visual-only presentation plus a very poor feel system, Mr. Chalk felt that any evaluation he made would be suspect.

Carl Crother of Rockwell made an informal presentation (follows this summary) on his work with equivalent systems applied to the B-1. This interesting presentation naturally led into further discussion of equivalent systems in general. One point in the presentation is that pilot comments indicate Level 1 flying qualities for configurations with time delays as high as 0.15 seconds. This apparently contradicts the value of 0.1 seconds previously proposed (see e.g. Hodgkinson in AFFDL-TR-78-171). A'Harrah suggested that the problem is with the algorithm to predict rating as well as the time delay. A mechanical system does not meet the phase lag requirement of 3.5.3* without augmentation. Therefore, there are the effects of different time delays to consider. It was also pointed out that there is still a possibility that allowable equivalent time delays for Class III aircraft will be different from those for Class IV aircraft. It should be noted that all the previous published work has been for Class IV configurations and should be used in that context.

---

*MIL-F-8785B, paragraph 3.5.3, Dynamic characteristics, contains such requirements in the form of maximum phase lag of control surface deflection to pilot input. MIL-F-8785C revises this requirement to include also include maximum equivalent time delays

Some of the "problems" of the equivalent system approach were voiced. A different equivalent system is required for gust inputs than for control inputs. Twisdale mentioned minimization problems in obtaining the "best" equivalent system. Crother added that a large part of his effort had been the software development in minimizing the cost function. A'Harrah countered by saying in NASC and McAir experience with the use of equivalent systems, a flexible approach to the cost function is required. The simple cost metric is only a part of the answer.

Schuler suggested that the problems of matching an equivalent system to an actual response were analogous to the problems of parameter identification. In general, one variable is required for each degree of freedom; it may be possible to match the time response but there are other considerations; and variables other than pitch attitude response need to be considered for the longitudinal axis. McAllister extended those comments using his experience with CCV configurations. As an example Maneuver Enhancement quickens the normal acceleration response relative to the pitch response. The two responses do not necessarily have the conventional relationship. The pilot task is the first consideration in determining which variable, or variables, to match with an equivalent system. Moorhouse stated that the use of the equivalent system approach in the specification, at this time, was an attempt to upgrade MIL-F-8785B and cure some deficiencies. MIL-F-8785B contains requirements on the short-period mode, for example, that can now be applied to the equivalent short-period response of higher-order systems. All modal requirements will now be applied to equivalent parameters, assuming the configuration flies in a "conventional manner". The change will not allow the specification to be applied to configurations, such as CCV airplanes, that it did not apply to before. Finally, Hodgkinson stated that a primary use of equivalent systems at McAir was to obtain a better understanding of the higher-order responses. For example, an early application of equivalents at MCAIR was to the maneuver enhancement CCV mode. The new equivalent flight path time constant is a direct measure of response quickening, and a separate application of MIL-F-8785 requirements to the pitch and normal load factor responses, matched separately, is effective. This is described in MCAIR Paper 1976-009, presented at the 7th Pittsburgh Conference on Modeling and Simulation in 1976. Equivalent systems should not be construed as an inflexible mould into which all dynamics should be forced. Equivalents, properly interpreted, are merely a way of extracting simple flying qualities parameters from complicated dynamics.

Schuler questioned the approach of specifying an equivalent time delay, pointing out that the data base for the short-period requirements in MIL-F-8785B included some time delay. Moorhouse agreed, adding that one potential benefit of Mayhew's criteria had been the possibility of trading off time delay with other parameters. The use of a time delay value in MIL-F-8785C was, in effect, doing what was suggested, i.e. putting a bound on the equivalent time delay for which the existing data applied. A'Harrah added that the current data base does support a single value of equivalent time delay [with the previously-mentioned qualification of being derived from data on Class IV configurations].

A change of subject was introduced by Siewert - he suggested that MIL-F-8785C is the last paper specification. Use of OMB Circular A190 would dictate performance specifications as the only solution. He cited the example of the F-111B specification - it incorporated the latest flying qualities criteria, which later turned out to require modification. The moral may be that too precise a specification is a mistake. Chalk raised the question of whether the use of such specifications would take the need off the government to sponsor research. McAllister added the thought that engineers can do a good job of design if they know what is required. The problem then becomes one of stating the requirements in terms the engineers can understand. As an afterthought: that theme may be extended by stating that the problem lies in defining the requirements in terms that everybody understands, engineers of different disciplines and terminology, management, procrurement, etc. .

Twisdale commented on the recent programs to obtain flying qualities data for landing approach, such as LAHOS. The work done at the AF Flight Test Center seems to indicate that air-to-air tracking is a more demanding task than landing approach. The Handling Qualities During Tracking (HQDT) technique was developed to fully exercise the airplane. In answer to a question, Twisdale asserted that the technique is not just oriented towards the pitch axis, but also will uncover lateral-directional problems. There is still a problem, however, with the "super sharp pilot" who may recognize and compensate for deficiencies in an airplane's flying qualities, so that the tracking performance measurements are misleading. A study of pilot comments, and maybe even an analysis of his dynamics, is required to get the total story.

The status of pilot-induced oscillation (PIO) requirements was requested. The draft MIL-F-8785C contains the suggested criteria of Ralph Smith (see AFFDL-TR-77-57). Smith added that he was trying to write a system specification, which the requirement in MIL-F-8785B, paragraph 3.5.3, was not. He felt that his phase criterion could be integrated with a revision of 3.5.3. The pilot time delay used was based on a correlation of the results for both the T-38 and YF-12. A'Harrah suggested that more validation was required, and Smith added that he had not had a chance to screen 'good configuration' against the criteria. Twisdale stated that the PIO criteria were used at AFFTC in explaining an F-15 characteristic. Hodgkinson points out that the F-15 characteristic is predicted very clearly by the modal requirements of MIL-F-8785. As described in AFFTC-TR-76-48, the pitch oscillations occur at supersonic conditions with augmentation off, where short period damping ratio is around .10. The augmented F-15 is in Level 1 and does not experience the oscillations. Therefore the unaugmented F-15 experience definitely does not justify the need for the PIO criterion. McAllister added that he saw the need for using the criteria as early as possible in the design phase.

Acceptance of relaxed stability was questioned, the draft MIL-F-8785C still allow an instability with time to double amplitude greater than 6 seconds. A'Harrah stated his opinion that definite benefits would have to be demonstrated for anything more unstable than a neutral maneuvering margin.

Schuler commented on the continually growing complexity of modern systems. As an example he cited the many unanswered questions pertaining to rate command/attitude hold functions - by definition a nonlinear system with the controlled and uncontrolled responses different. He ended with a plea for some control over what a digital computer should be asked to do, or allowed to do.

The discussion wound down with one or two random comments, such as pilot-tailored flying qualities (?).

In summary the workshop was well attended, with a mix of government and industry personnel. The use of equivalent systems received the majority of attention, in part because of their use in the draft MIL-F-8785C. The justification and substantiation has been published a number of times. The discussion of "problems" in this workshop is positive in recognizing that still more work is required. The list might include: (i) equivalent system requirements need to be formulated for Classes of airplanes other than fighters; (ii) further consideration of lateral-directional axes is required; (iii) extension is required to 6 degree-of-freedom (CCV) applications; (iv) further consideration of the frequency range required for matching the equivalent system, possibly defining a range of pilot-frequency content for each particular task.

Another discussion topic without an answer is the subject of performance requirements. The problem here is specifying required performance with a human pilot in the loop, plus acceptability to that pilot. Compliance demonstration becomes a problem of choosing the pilot, or pilots, to do the flight tests. Signal Corps Specification No. 486 is frequently cited as a model of a performance specification. The total task, however, was solely to fly - a fairly simple requirement to judge, Since this is an involved subject with many aspects and many opinions, it may well be an ideal subject for a future Flying Qualities Symposium.

ATTENDEES

R. A'Harrah	NAVAIR
Dan Biezad	USAFTPS/Edwards
Lt J. Browne	AFFDL/FGC
C. R. Chalk	Calspan
C. A. Crother	Rockwell Int'l
R. A. Curnutt	Beech Aircraft
H. E. Hatcher	General Dynamics
John Hodgkinson	McAir
Doug Kirkpatrick	NAVAIR
T. D. Lewis	AFFDL/FGL
Paul Martorella	Grumman
J. D. McAllister	General Dynamics
Walter E. McNeill	NASA/Ames
D. J. Moorhouse	AFFDL/FGC
John Richardson	Rockwell Int'l (Columbus)
J. M. Schuler	Boeing/BMAD
Ray Siewert	OSD/USDRE
R. H. Smith	SRL/Self
Mark Stifel	NADC
Tom Twisdale	AFFTC

EQUIVALENT SYSTEM MODELLING

OF THE AUGMENTED B-1

BY

C.A. CROTHER*- B. GABELMAN*

Recent, advanced aircraft have exhibited flying qualities characteristics which do not fit the mold of the MIL-F-8785B specifications. The high order system (HOS) dynamics of these vehicles occur because complex flight control systems and/or unusual vehicle response modes are utilized. To render judgement on the flying qualities of these vehicles some method must be provided to describe these high order dynamics in terms correlatable to 8785B specifications. In recent years, such a method has attracted much attention. The concept of equivalent system modelling has shown promising results (Ref. 1) and, in fact, has been recommended as a method for assessing 8785B specification compliance (Ref. 2).

Most, if not all, of the equivalent system data described in the literature are based on fighter type aircraft. A brief examination of the applicability of the equivalent system concept to a large flexible aircraft, like the B-1, was made and the results are described below. The above comments are summarized in Chart 1.

A block diagram of the B-1 longitudinal flight control system is shown in Chart 2. Elements of interest are: 1) the parallel mechanical and electrical command paths, 2) stick prefilter, 3) the structural low pass and notch filter in the feedback path and 4) the summed pitch rate and normal acceleration signals in the feedback with compensation.

Five flight conditions were examined and they are listed in Chart 3. Condition 1 is considered Category C, Conditions 2, 3 and 5 are Category A, while Condition 4 can be considered Category B.

The high order transfer functions for pitch rate to pitch input force for the 5 flight conditions are listed in Chart 4. The order is: numerator 9th, the denominator 12th.

The low order system (LOS) model used for the matching is shown in Chart 5. The mismatch measure is shown as the error algorithm and a predicted pilot rating algorithm is also listed. The rating algorithm is taken from Ref. 2 and is based on fighter aircraft data obtained in flying qualities flight test experiments (Ref. 3). Two sets of model data for the B-1 are shown, one with the L_{α} term fixed at the aircraft value and the other with L_{α} being a variable in the matching process. The observations to be made

* Flight Controls Analysis - North American Aircraft Division
Rockwell International

are: 1) equivalent time delays are large except for the L_α free Condition 1, 2) the L_α fixed and free values are close except for Condition 1, 3) the equivalent damping ratios and frequencies are reasonable and 4) the mismatch values are acceptable.

The technique used for the frequency response curve fitting was a combination of search and minimization procedures. Approximate relationships were derived for k (the gain), T (the time delay) and ωn (the undamped frequency) based on the HOS data in the 0.1 to 10.0 rad/sec frequency range. A square grid search was implemented using the remaining two unknowns, L_α and ζ. The best guess (minimum error) resulting from the above relationships and search was then used as the starting point for a minimization routine based on a quasi-Newton method (Ref. 4).

Examples of the curve fits obtained, in terms of Bode plots and transient responses are shown in Charts 6 through 15.

Charts 16 and 17 compare the short period frequencies obtained from the HOS and LOS data and presented in the 8785B ωn_{sp} vs. n/α format. For several of the flight conditions, flight test measured augmented short periods are also depicted. The n/α 's used are based on the aircraft's analytical aerodynamic derivatives. For Conditions 3 and 5, the LOS data with L_α fixed do not meet the Level I requirements. The LOS L_α free data do meet the requirements but if n/α is recomputed based on $n/\alpha = \frac{U}{g} \times L_\alpha$ free, the points move as indicated and, except for Condition 4, become unacceptable.

The known B-1 flying qualities as measured by simulation and flight test pilot ratings are listed in Chart 18. In each condition, the ratings are Level I. The equivalent system data indicate unacceptability based on the large time delays (Level I requires $T < .10$ sec, Ref. 2), the ωn_{sp} vs. n/α data and the pilot rating predictive algorithm (admittedly derived from fighter aircraft data). These results clearly indicate the necessity for continued development of the equivalent system criteria for large aircraft applications.

Since the B-1 control system has a fairly large stick prefilter (τ = .5sec), an examination was made of the prefilter's effect on the equivalent time delay. Chart 19 presents the results. The removal of the prefilter does reduce the time delay but not enough to bring it to Level I. The plot shown on the bottom of Chart 19 illustrates the need for the prefilter. Without the prefilter the pilot tends to excite the B-1's structural modes in an unacceptable fashion.

In summary, this study shows the B-1 exhibits HOS characteristics, the LOS match predicts poor pilot ratings which are at variance with known B-1 ratings and, consequently, more work must be directed to B-1 type vehicle criteria.

REFERENCES

1. Hodgkinson, John - "Equivalent Systems Approach for Flying Qualities Specification", SAE Aerospace Control and Guidance Systems Committee Meeting, Denver, Colo., March 1979.

2. A'Harrah, R. C., J. Hodgkinson and W. J. La Manna, - "Are Today's Specifications Appropriate for Tomorrow's Airplanes?", AGARD Flight Mechanics Panel Meeting on Stability and Control, Ottawa, Canada, September 1978.

3. Neal, T. P. and Smith, R. E. - "An In-flight Investigation to Develop Control System Design Criteria for Fighter Airplane", AFFDL-TR-70-74, December 1970.

4. "FORTRAN Subroutines for Minimization by Quasi-Newton Methods", International Mathematicsand Statistics Library based on Report R7125 AERE, Harwell, England, June 1972.

EQUIVALENT SYSTEM MODELLING OF THE AUGMENTED B-1

AFFDL FLYING QUALITIES WORKSHOP
OCT 9-10, 1979

C. A. CROTHER
B. GABELMAN
NORTH AMERICAN AIRCRAFT DIVISION
ROCKWELL INTERNATIONAL

EQUIVALENT SYSTEM MODELLING OF THE AUGMENTED B-1

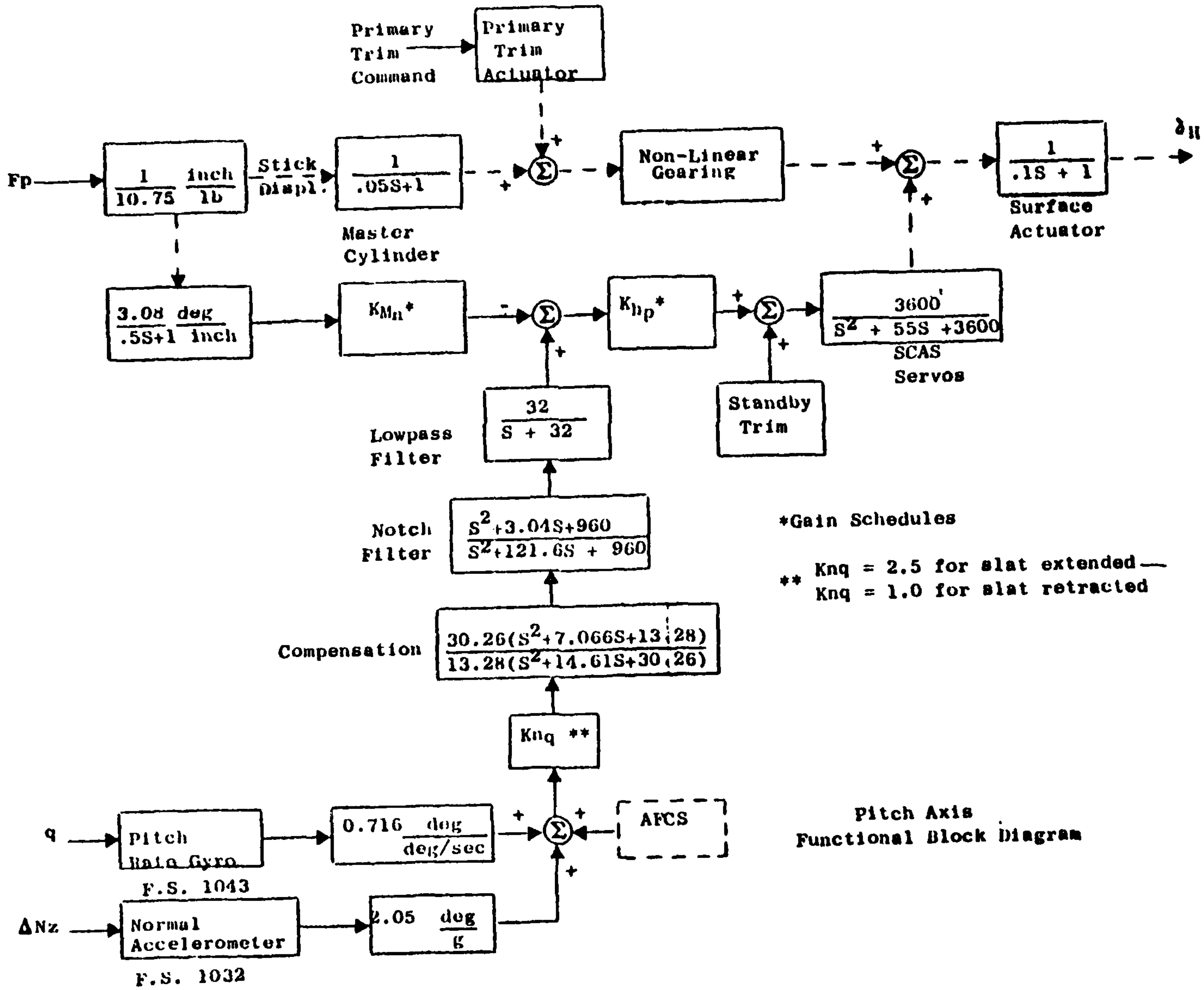
BACKGROUND

- RECENT STUDIES HAVE SHOWN LOW ORDER SYSTEM MATCHING HAS LED TO FLYING QUALITIES PREDICTIONS CORRELATABLE TO CURRENT MIL-F-8785B SPECIFICATIONS
- THE DATA UTILIZED IN STUDIES TO DATE WERE FROM FIGHTER TYPE AIRCRAFT

OBJECTIVE

- TO TEST THE LOW ORDER SYSTEM CONCEPT DESCRIBED IN THE LITERATURE USING B-1 DATA

B-1 PRIMARY FLIGHT CONTROL SYSTEM - LONGITUDINAL



*Gain Schedules

** Knq = 2.5 for slat extended
Knq = 1.0 for slat retracted

Pitch Axis
Functional Block Diagram

FLIGHT CONDITIONS

1 Landing Approach

2 Air Refueling

3 Low Altitude Penetration

4 Supersonic, Medium Altitude

5 Low Altitude Withdrawal

B-1 PITCH RATE TO STICK FORCE TRANSFER FUNCTION $\left(\frac{DEG/SEC}{LB}\right)$

FLT. COND.	
1	$\dfrac{119.1(113.1)(32)(12.11)(8.487)(1.47)(2.498)(4.72)(26.1,58.1)}{(113.4)(20)(2.34)(2)(27.75,53.1)(25.6,6.97)(4.13,4.37)(2.5,2.19)}$
2	$\dfrac{254.8(113.1)(32)(12.11)(.629)(8.49)(2.5)(3.19)(26.9,55.3)}{(113.3)(20)(2.08)(2)(27.7,53.2)(25.3,5.17)(4.97,3.93)(1.59,2.12)}$
3	$\dfrac{226.6(113.1)(32)(12.11)(.75)(8.49)(2.5)(3.78)(26.6,56.35)}{(113.4)(20)(2.25)(2)(27.8,53.1)(25.76,8.2)(2.8,3.79)(3.24,3.33)}$
4	$\dfrac{359.3(113.1)(32)(12.11)(.31)(8.49)(2.5)(3.04)(26.98,55.04)}{(113.4)(20)(2)(2)(27.77,53.12)(25.7,7.54)(3.89,3.8)(1.92,3.20)}$
5	$\dfrac{173.5(113.1)(32)(12.11)(.62)(8.49)(2.5)(3.36)(26.8,55.6)}{(113.3)(20)(2.1)(2)(27.66,53.22)(24.97,2.70)(5.62,3.76)(1.38,1.76)}$

$(A) \equiv (S+A)\;,\quad (B,C) \equiv (S + B \pm jC)$

LOW ORDER SYSTEM MATCHING

MODEL : $$\frac{K(S+L_\alpha)e^{-TS}}{S^2+2\zeta\omega_n S+\omega_n^2}$$

ERROR : $$\Sigma(A_R-A_M)^2+0.02(\phi_R-\phi_M)^2$$

PILOT RATING ALGORITHM : $$PR=5.16+18.5T+\frac{.56L_\alpha}{2\zeta\omega_n}-.61\zeta\omega_n+.02\omega_n^2$$

	L_α Fixed						L_α Free					
FLT COND	L_α	K	T	ζ	ω_n	Error	L_α	K	T	ζ	ω_n	Error
1	1.56	.86	.158	.69	2.22	31	27.3	.18	.07	.55	4.08	2.7
2	.66	1.59	.154	.57	1.98	33	1.0	1.43	.143	.45	2.23	23
3	.83	1.68	.163	.59	2.85	40	1.3	1.44	.151	.44	3.17	29
4	.36	2.53	.163	.52	2.74	43	.40	2.57	.161	.49	2.78	41
5	.67	1.04	.151	.55	1.69	32	1.1	.94	.140	.43	1.95	22

MARTINS CASE 1 (MODEL=SOLID, ROOT FIXED)

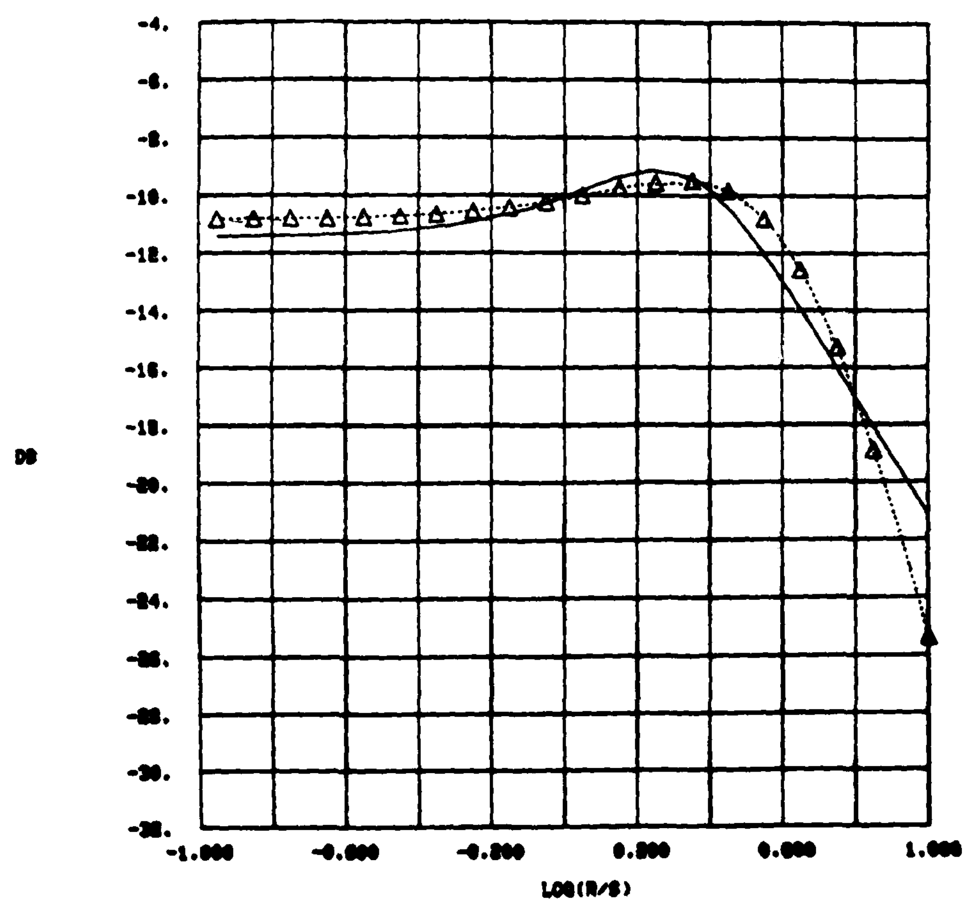
FLT COND 1 $\dot{\theta}/F_P$ FREQUENCY RESPONSE

L_α Fixed

Error = 31

Δ···Δ HOS

—— LOS

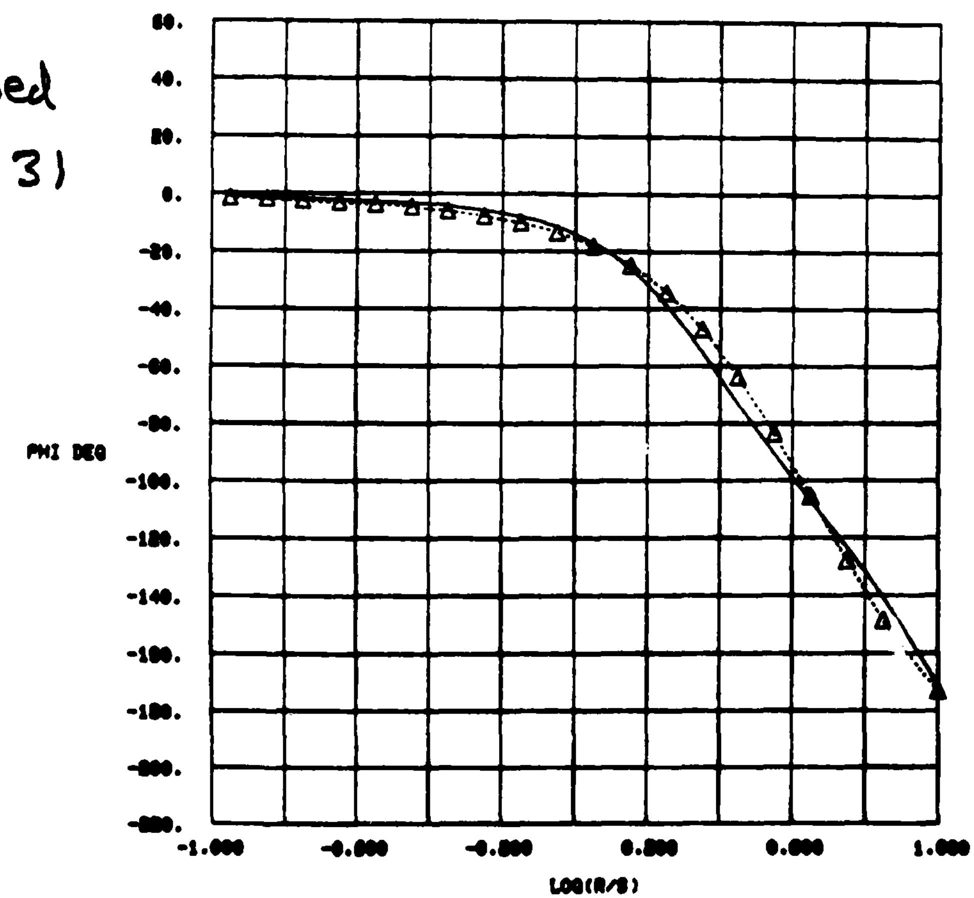


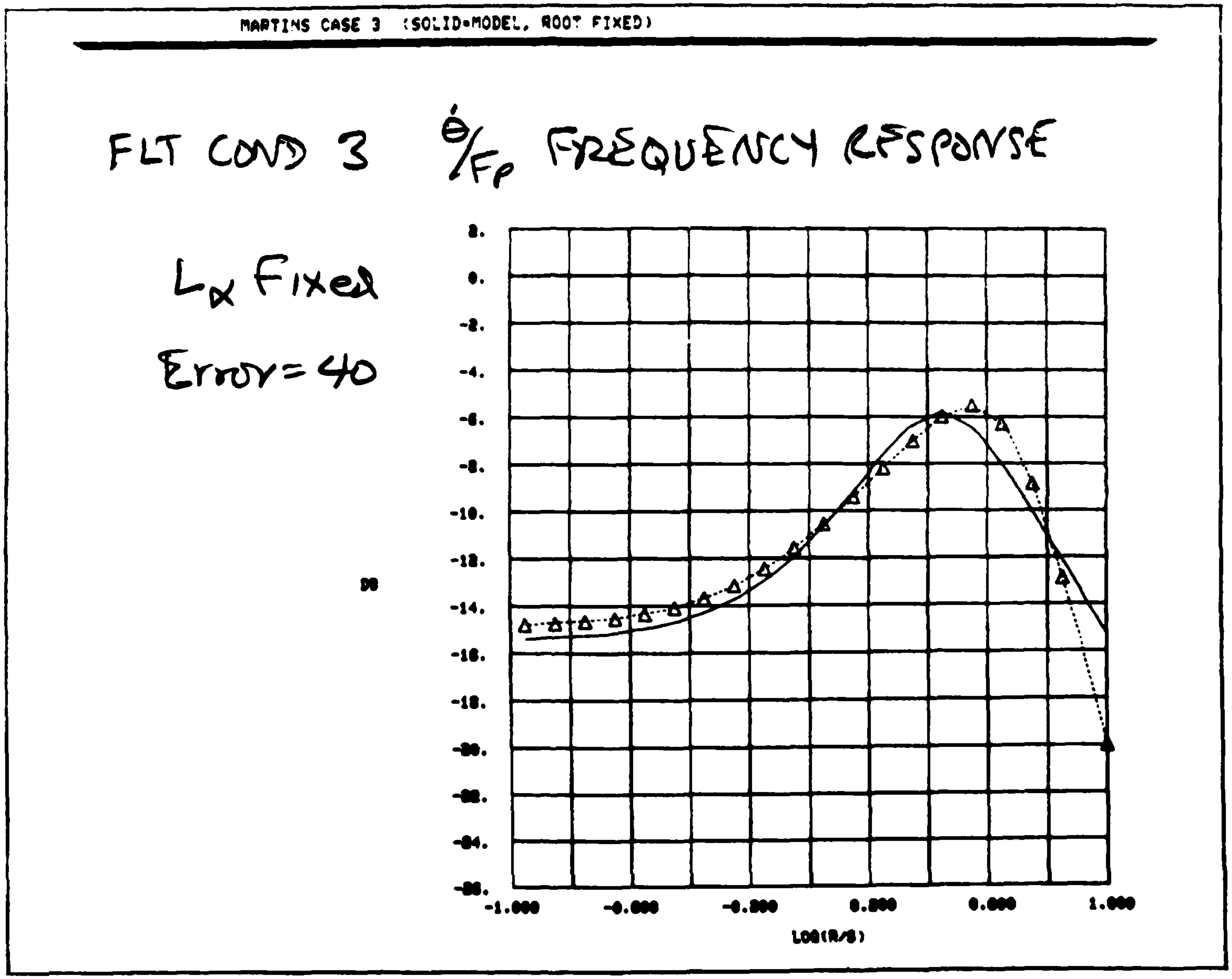
MARTINS CASE 1 (MODEL=SOLID, ROOT FIXED)

FLT COND 1 $\dot{\Phi}/F_p$ FREQUENCY RESPONSE

L_α Fixed

Error = 31



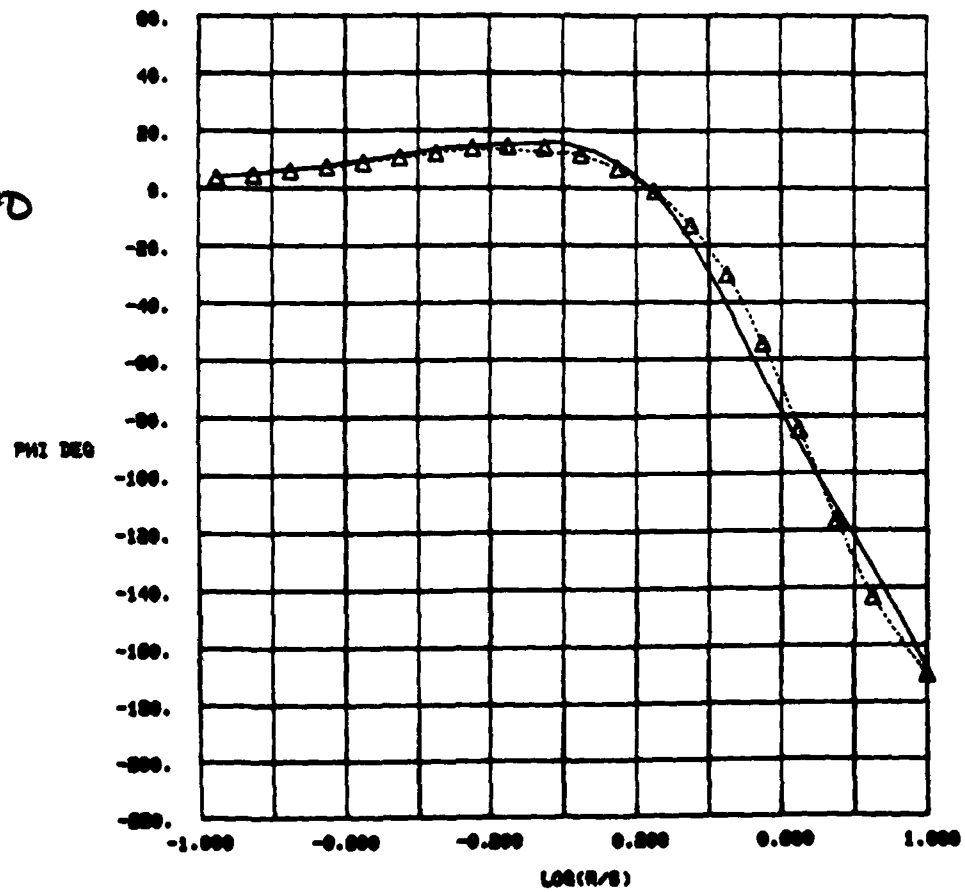

MARTINS CASE 3 (SOLID-MODEL, ROOT FIXED)
FLT COND 3
$\dot{\theta}/F_P$ FREQUENCY RESPONSE
L_α Fixed
Error = 40
DB
LOG(R/S)

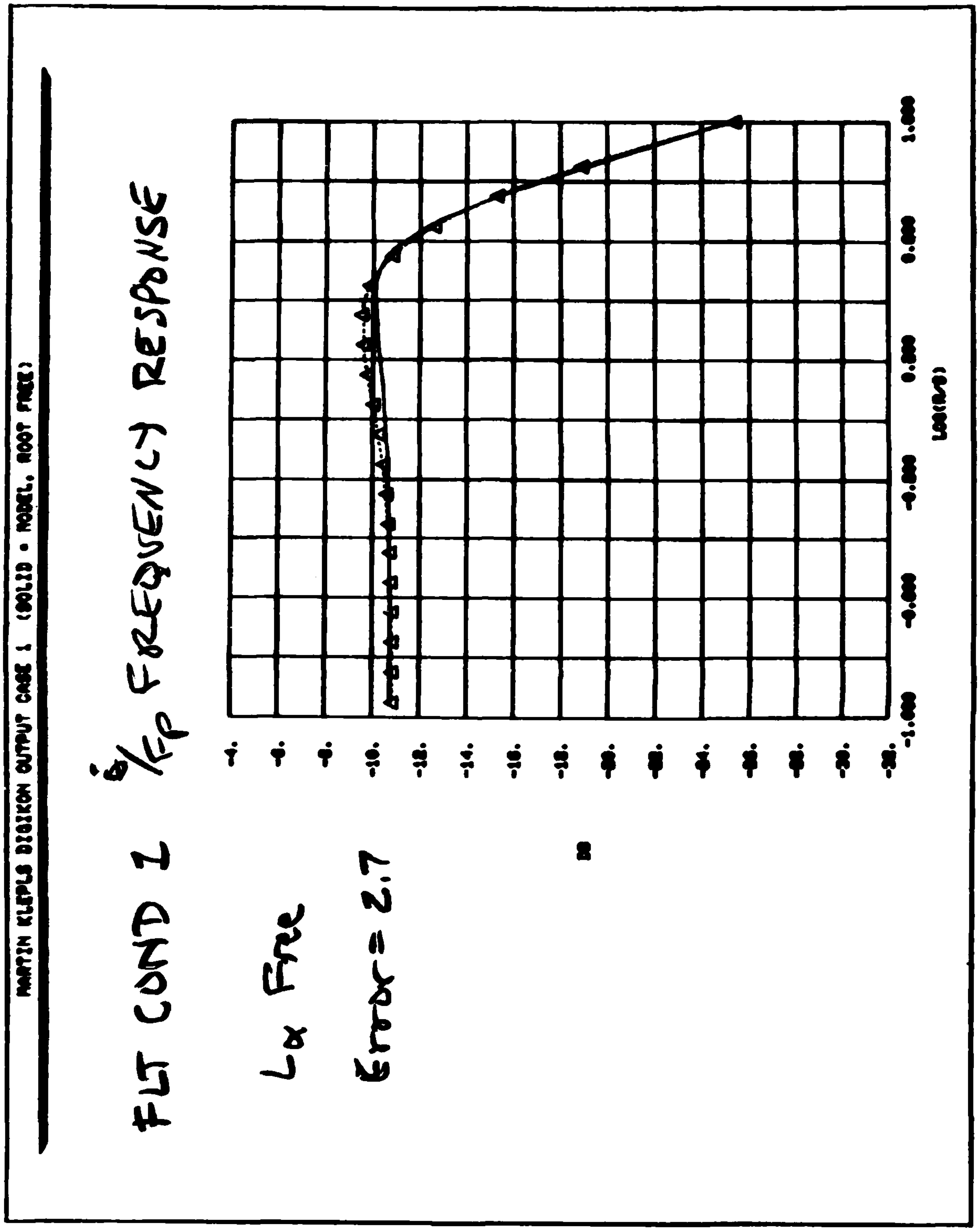
MARTINS CASE 3 (SOLID-MODEL, ROOT FIXED)

FLT COND 3 $\dot{\theta}/F_p$ FREQUENCY RESPONSE

L_α Fixed

Error = 40



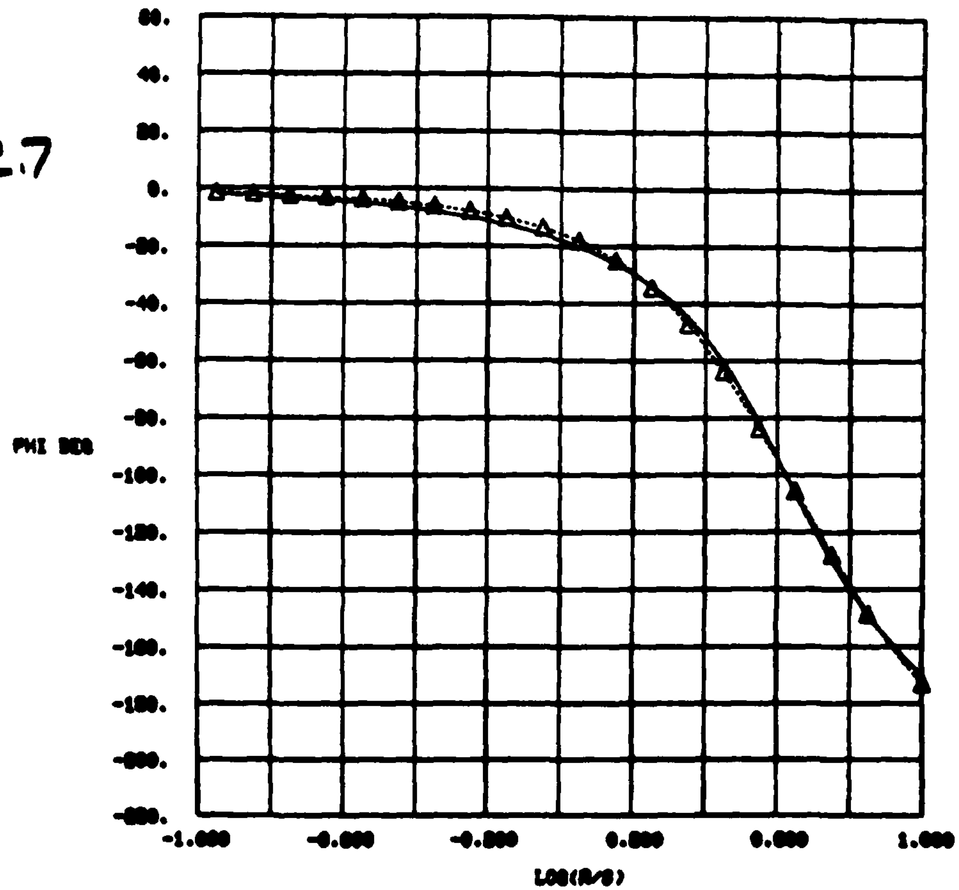

MARTIN KLEPLS DIGIKON OUTPUT CASE 1 (SOLID = MODEL, ROOT FREE)
FLT COND I
$\dot{\theta}/F_p$ FREQUENCY RESPONSE
L_α Free
Error = 2.7
DB
LOG(R/S)
-1.000
1.000

MARTIN KLEPLS DIGIKON OUTPUT CASE 1 (SOLID = MODEL, ROOT FREE)

FLT COND 1 $\dot{\theta}/F_p$ FREQUENCY RESPONSE

L_α Free

Error = 2.7

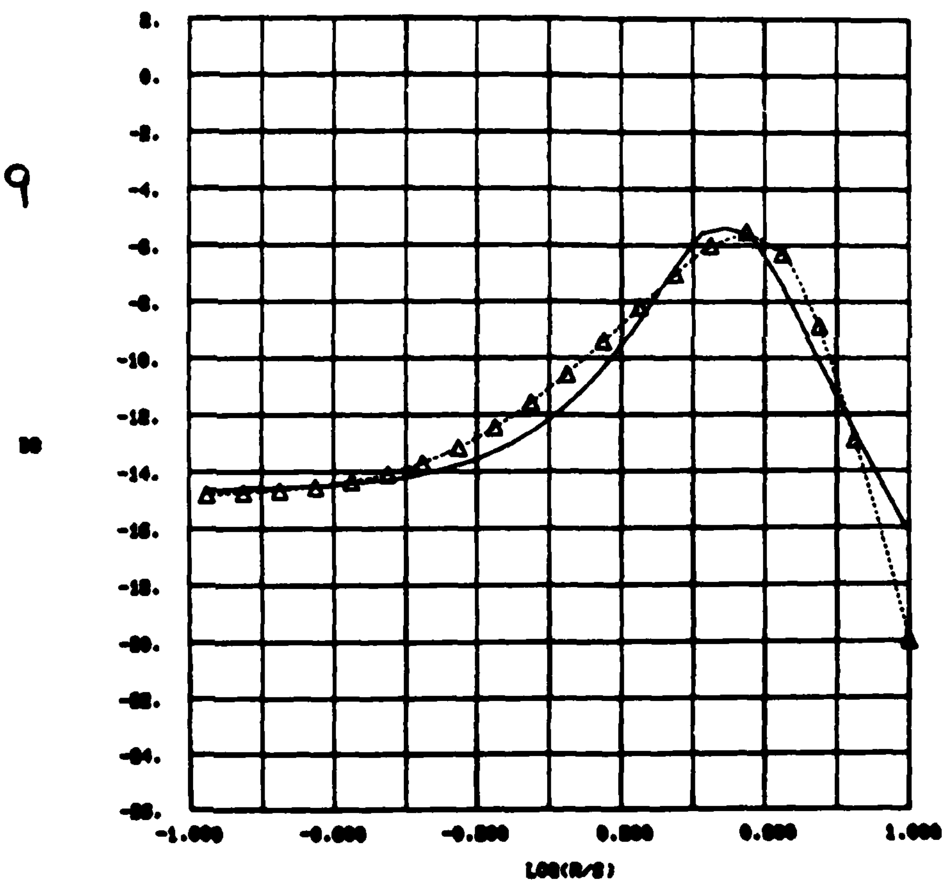


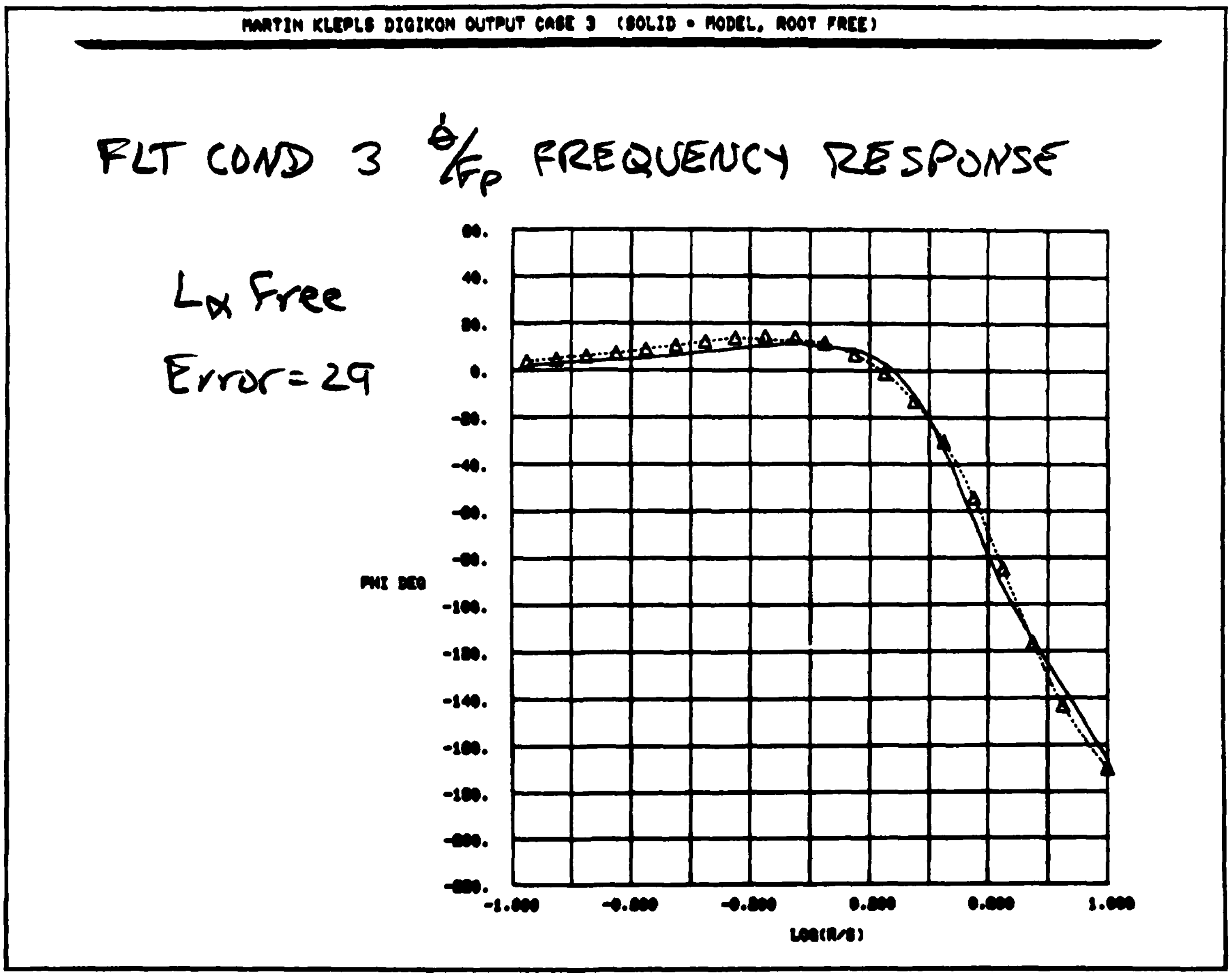
MARTIN KLEPLS DIGIKON OUTPUT CASE 3 (SOLID = MODEL, ROOT FREE)

FLT COND 3 $\dot{\theta}/F_p$ FREQUENCY RESPONSE

L_α Free

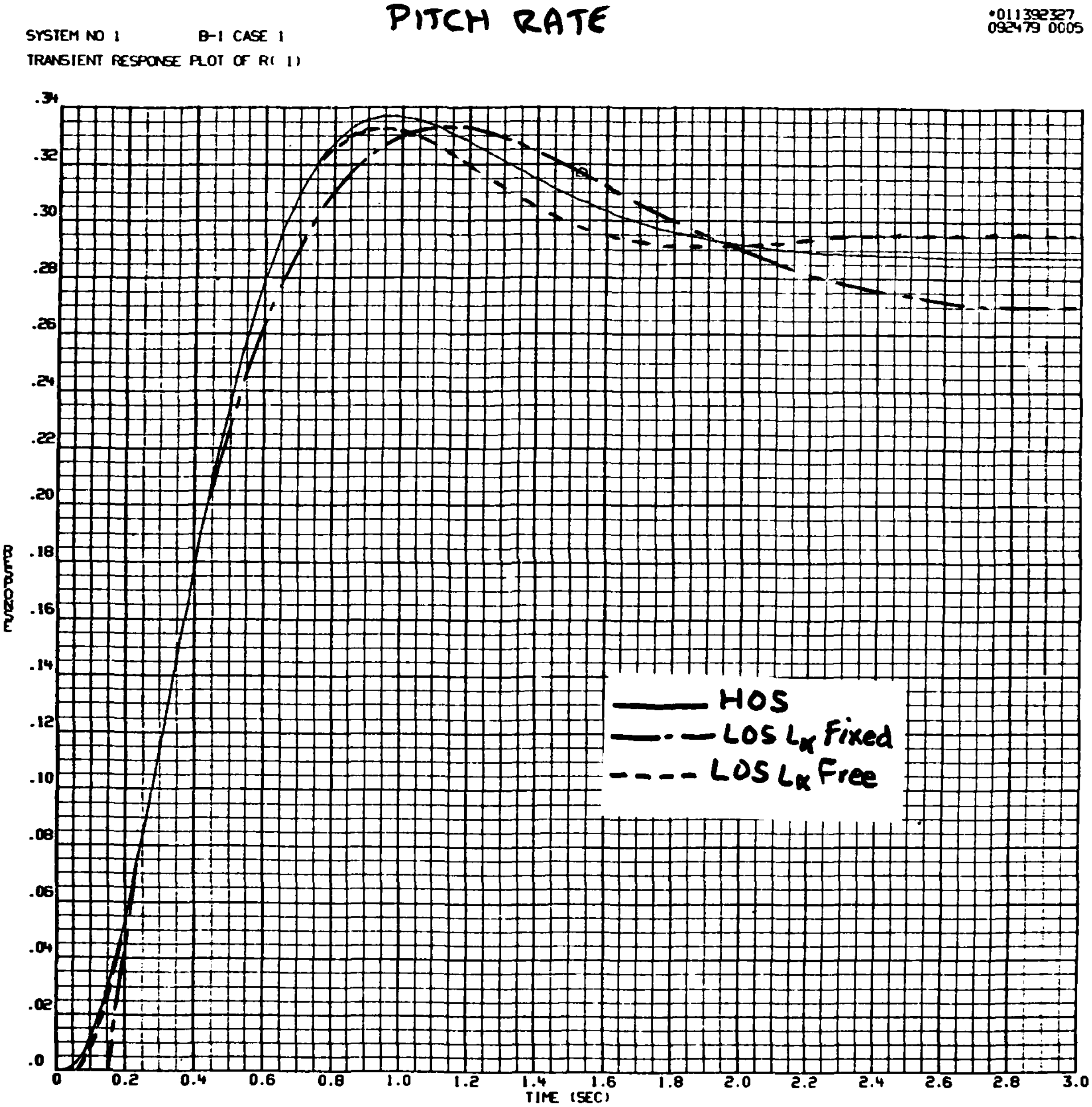
Error = 29




MARTIN KLEPLS DIGIKON OUTPUT CASE 3 (SOLID = MODEL, ROOT FREE)
FLT COND 3 $\dot{\phi}/F_p$ FREQUENCY RESPONSE
L_α Free
Error = 29
PHI DEG
LOG(R/S)

FLT COND 1 - RESPONSE MATCHES

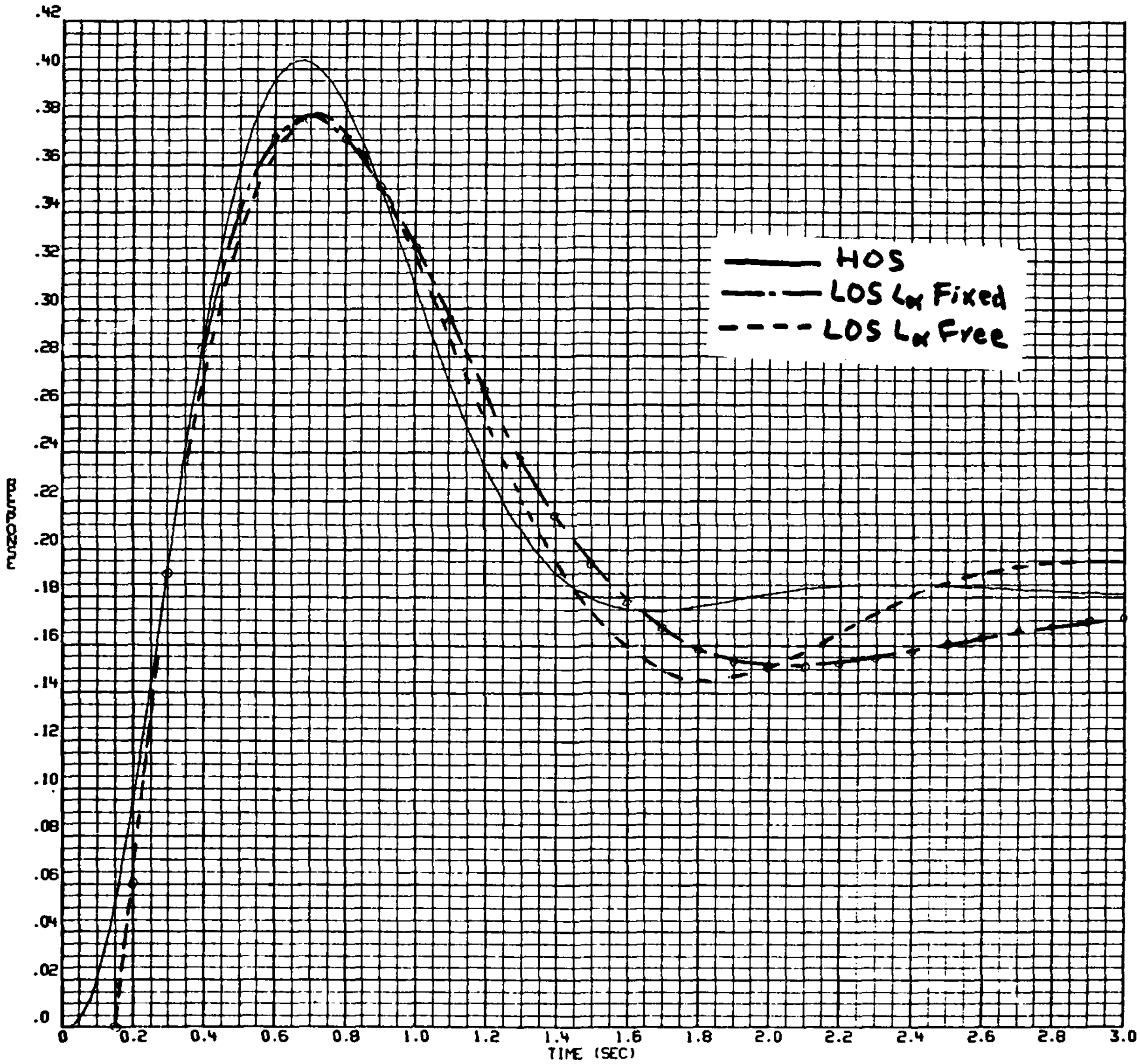
PITCH RATE

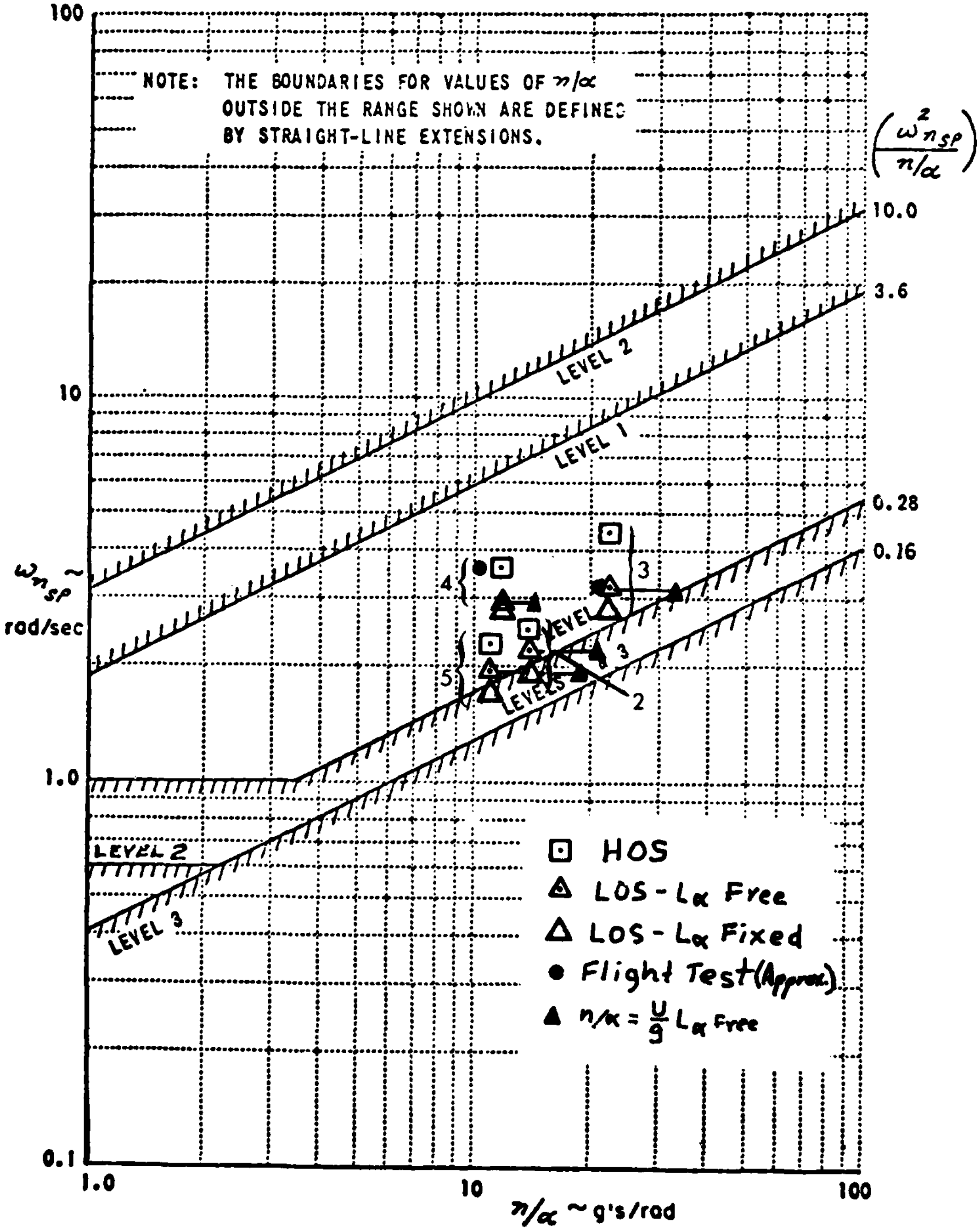


FLT COND 3 - RESPONSE MATCHES PITCH RATE

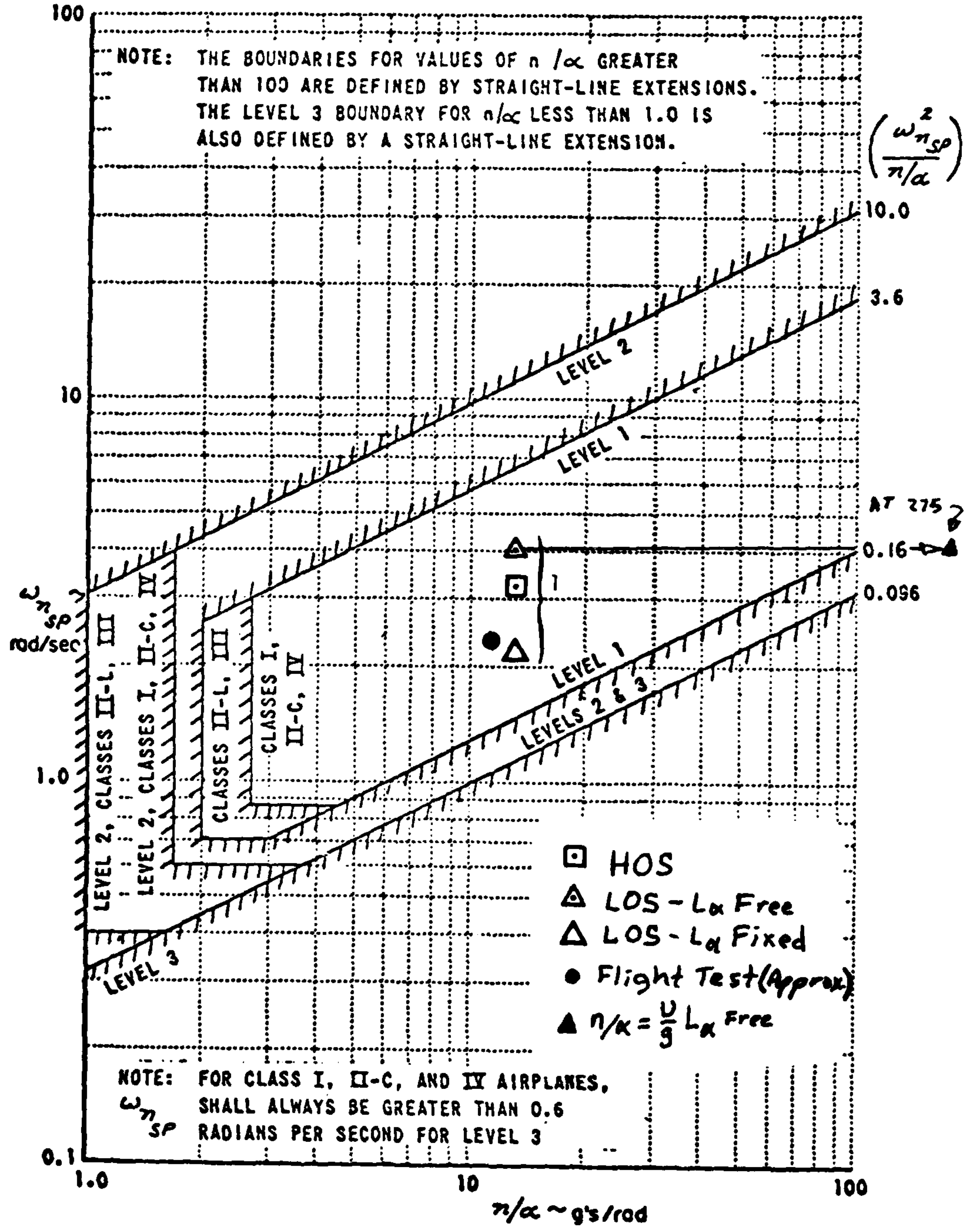
SYSTEM NO 3 B-1 CASE 3
TRANSIENT RESPONSE PLOT OF R(1)

*011113923
092179 0011





Short-Period Frequency Requirements - Category A Flight Phases



Short-Period Frequency Requirements - Category C Flight Phases

PREDICTED & ACTUAL PILOT RATINGS

FLT. COND.	LOS PREDICTION	SIMULATION & FLIGHT TEST RATINGS
1	8.8	2.7
2	7.6	2.8
3	7.4	2.5*
4	7.5	3.3
5	7.7	2.3*

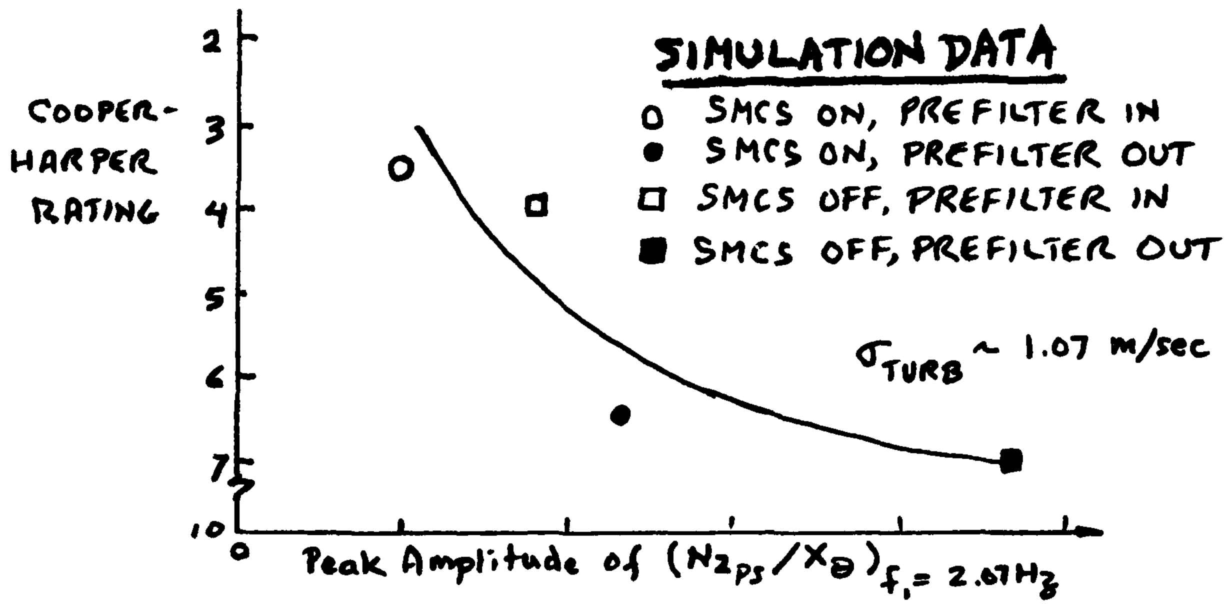
* RATINGS DURING MANUAL TERRAIN FOLLOWING FLIGHT TESTS

GENERAL FLT TEST OBSERVATIONS

- GOOD AIRPLANE TO FLY
- HAS PERFORMED WELL DURING PRECISION FLYING
- OVERALL FLYING QUALITIES RATED BY PILOTS AS SATISFACTORY TO EXCELLENT

LOS MATCHING - NO STICK PREFILTER

	Prefilter			No Prefilter		
FLT COND	T	P.R.	ERROR	T	P.R.	ERROR
1	.068	8.8	2.7	.10	6.6	6.6
2	.143	7.6	23	.12	7.0	14
3	.151	7.4	29	.12	6.8	15
4	.161	7.5	41	.14	7.2	24
5	.140	7.7	22	.12	7.0	11



SUMMARY

- B-1 EXHIBITS HIGH ORDER CHARACTERISTICS IN LONGITUDINAL CONTROL AXIS
- LOW ORDER SYSTEM USED DOES NOT PROVIDE A GOOD MATCH & PREDICTS POOR RATINGS
- B-1 SIMULATION & FLIGHT TEST EVALUATIONS ARE SIGNIFICANTLY DIFFERENT THAN LOW ORDER SYSTEM PREDICTIONS
- ATTENTION MUST BE DIRECTED TO LOW ORDER SYSTEM EQUIVALENCY CRITERIA FOR B-1 TYPE AIRCRAFT

JOHN HODGKINSON, McDonnell Douglas: The work which you referenced was based on T-33 data. Would you like to comment on the relevancy of such fighter type data to your findings based on the B-1?

ANSWER: It is certainly true that the referenced work was generated using T-33 data. But that is part of the reason for my looking into the B-1 data. No equivalent system data had been generated for large aircraft but criteria based on the T-33 work were being considered for MIL-F-8785C inclusion. Particularly in regards to equivalent time delay, the implication of Ref. 2 was that the time delay criterion of .10 sec was not restricted to aircraft class. I think the B-1 data just points up the need for more work in equivalent system criteria development for Class III aircraft.

APPENDIX A

FLYING QUALITIES SYMPOSIUM ATTENDANCE

NAME	AFFILIATION
R.C. A'Harrah	Nav Air
Ron Anderson	AFFDL/FG
W.H. Ashbaugh	ASD/ENFTC
Calvin Bayley	General Dynamics/Fort Worth
Dr. Walter Beam	OSAF/SAFALR
Willie S. Bennett	General Dynamics/Fort Worth
Don Berry	NASA Dryden
Maj Dan Biezad	USAF Test Pilot School/TENC Edwards
1Lt Jack Browne	AFFDL/FGC
Jim Buckley	McDonnell Aircraft/St Louis
Tullio Calanducci	ASD/ENFTC
John W. Carlson	AMST SPO/ASD
Charles Chalk	Calspan
Jimmie Chin	Grumman Aerospace
Duane Choo	Northrop, Hawthorne, CA
Tom Cord	AFFDL/FGC
Lt Robert Crombie	AFFDL/FGC
Carl Crother	Rockwell International
R.A. Curnutt	Beech Aircraft Corp.
Steven B. Dron	AFFDL/FGLB
Bill Gaugh	Northrop
Frank George	AFFDL/FGC
Loyal Guenther	McDonnell Douglas Corp.
Hayden E. Hatcher	General Dynamics/Fort Worth
John Hodgkinson	McDonnell Aircraft
J.E. Iles	Grumman Aerospace
Don E. Johnston	Systems Technology Inc.
Craig R. Jones	4950 TESTW/FFM
Doug Kirkpatrick	Naval Air System Command
William H. Levison	BBN

APPENDIX A

FLYING QUALITIES SYMPOSIUM ATTENDANCE (Con't)

NAME	AFFILIATION
T.D. Lewis	AFFDL/FGL
Paul Martorella	Grumman Aerospace
Jack McAllister	General Dynamics/Fort Worth
Lonnie McCray	AFFDL/FGR
Walter E. McNeill	NASA Ames
Bob Meyer	Lockheed Georgia Co.
David Moorhouse	AFFDL/FGC
Dieter Multhopp	ASD/ENFTC
Edward D. Onstott	Northrop
William H. Pearson	AFAMRL/HEG
David M. Phillips	4950 TW/DOAB
Bob Radford	Calspan
John Richardson	Rockwell Int'l/Columbus, OH
W.W. Rickard	Douglas Aircraft/Long Beach, CA
Grady H. Saunders, Jr.	ARO, Inc./Arnold AFS
Dave Schmidt	Purdue University
John Schuler	Boeing
Naren Shah	Northrop
Ray Siewert	OSD/USDRE
James Silverthorn	AFIT/ENY
Tim Sweeney	ASD/ENFTC
Larry Taylor	NASA Langley
Brian W. Van Vliet	AFFDL/FI
Don West	Boeing
Tom Willen	Maverick SPO/ASD
R.J. Woodcock	AFFDL/FGC

☆U.S.Government Printing Office: 1980 — 657-084/22